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When and where did India and Asia collide?

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[1] Timing of the collision between India and Asia is the key boundary condition in all models for the evolution of the Himalaya-Tibetan orogenic system. Thus it profoundly affects the interpretation of the rates of a multitude of associated geological processes ranging from Tibetan Plateau uplift through continental extrusion across eastern Asia, as well as our understanding of global climate change during the Cenozoic. Although an abrupt slowdown in the rate of convergence between India and Asia around 55 Ma is widely regarded as indicating the beginning of the collision, most of the effects attributed to this major tectonic episode do not occur until more than 20 Ma later. Refined estimates of the relative positions of India and Asia indicate that they were not close enough to one another to have collided at 55 Ma. On the basis of new field evidence from Tibet and a reassessment of published data we suggest that continent-continent collision began around the Eocene/Oligocene boundary (~34 Ma) and propose an alternative explanation for events at 55 Ma.

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1. Introduction

[2] What happens when two continents collide? The collision between India and Asia is the largest active orogen in existence and provides the type example for interpreting older mountain systems, yet we believe that fundamental issues such as the timing of the initiation of collision "T_0" are poorly understood. Nevertheless, introductions to almost all discussions of Tibet-Himalayan geology from scientific papers through textbooks to television documentaries that mention the subject assume that this collision began at the start of the Eocene, circa 55 Ma.

[3] Early estimates of the timing of the India-Eurasia collision based on plate modeling noted a change in tectonics throughout Asia around the Eocene-Oligocene boundary [*Hodges*, 2000; *Molnar and Tapponnier*, 1975; *Patriat and Achache*, 1984; *Searle et al.*, 1987]. A sharp decline in eastern and central Indian ridge spreading rates [*Patriat and Achache*, 1984] and the attendant slowdown in India's northward migration [*Acton*, 1999; *Klootwijk et al.*, 1992a] were widely regarded as marking the inception of collision. Geophysical studies, principally of marine magnetic anomaly data, led to refinement of early estimates from ~40 Ma [*Patriat and Achache*, 1984] to the now generally accepted estimate for the timing of India's slowdown at 55–57 Ma [*Acton*, 1999; *Klootwijk et al.*, 1992a].

[4] Widespread consensus exists as to the nature of the geological evidence that might well constrain the timing of collision initiation and this is perhaps best summarized by *Searle et al.* [1988, p.117], who stated "The timing of terminal collision of the two plates is deduced from (i) the ending of marine sedimentation in the Indus Suture Zone (ISZ), (ii) the beginning of continental molasse sedimentation along the suture zone, (iii) the ending of Andean-type calc-alkaline magmatism along the Trans-Himalayan (Ladakh–Kohistan–Gangdese) batholith and (iv) the initiation of the major collision-related thrust systems in the Himalayan Ranges."

[5] Data available up to the mid-1990s indicated the cessation of marine sedimentation in the Tethyan Himalaya on the northern margin of India (Figure 1) occurred circa 52 Ma [*Rowley*, 1996]. The beginning of molasse sedimentation along the Tibetan part of the suture zone was regarded as Eocene (Yarlung Tsangpo [*Searle et al.*, 1987, Figure 9]) with initiation of deposition of the correlative Indus Molasse along the Indus suture also regarded as Eocene [*Searle et al.*, 1987, Figure 10]. Radiometric age data from the Gangdese batholith indicated the youngest calc-alkaline magmatism to be around 40 Ma [*Coulon et al.*, 1986; *Debon et al.*, 1986; *Maluski et al.*, 1982; *Schärer et al.*, 1984; *Xu et al.*, 1985]. In the 1980s, few data were available to constrain the initiation of major collision-related thrust systems in the Himalayan ranges, and knowledge of the relative ages of different systems upon the Tibetan Plateau was rudimentary.

[6] A first-order tectonic event such as continent-continent collision should rapidly generate significant responses detectable in the geological record such as those observed in extant juvenile or incipient collisions of considerably lesser magnitude. For example, the collision between the Luzon arc and Eurasia in Taiwan has resulted in uplift of a mountain chain to almost 4000 m since 5 Ma and the Plio-Pleistocene sedimentary record is littered with orogen-derived coarse clastic detritus [*Huang et al.*, 2000]. In collisions of greater magnitude the observable effects ought

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to be even more profound. Most researchers now favor initiation around 50–55 Ma [*Hodges*, 2000; *Molnar and Tapponnier*, 1975; *Patriat and Achache*, 1984; *Searle et al.*, 1987], although some [*Ding et al.*, 2005; *Yin*, 2006; *Yin and Harrison*, 2000] prefer an even earlier time ~70 Ma. However, as better constraints on the timing of predicted geological responses have become available a considerable temporal gap between the inferred timing of initiation and

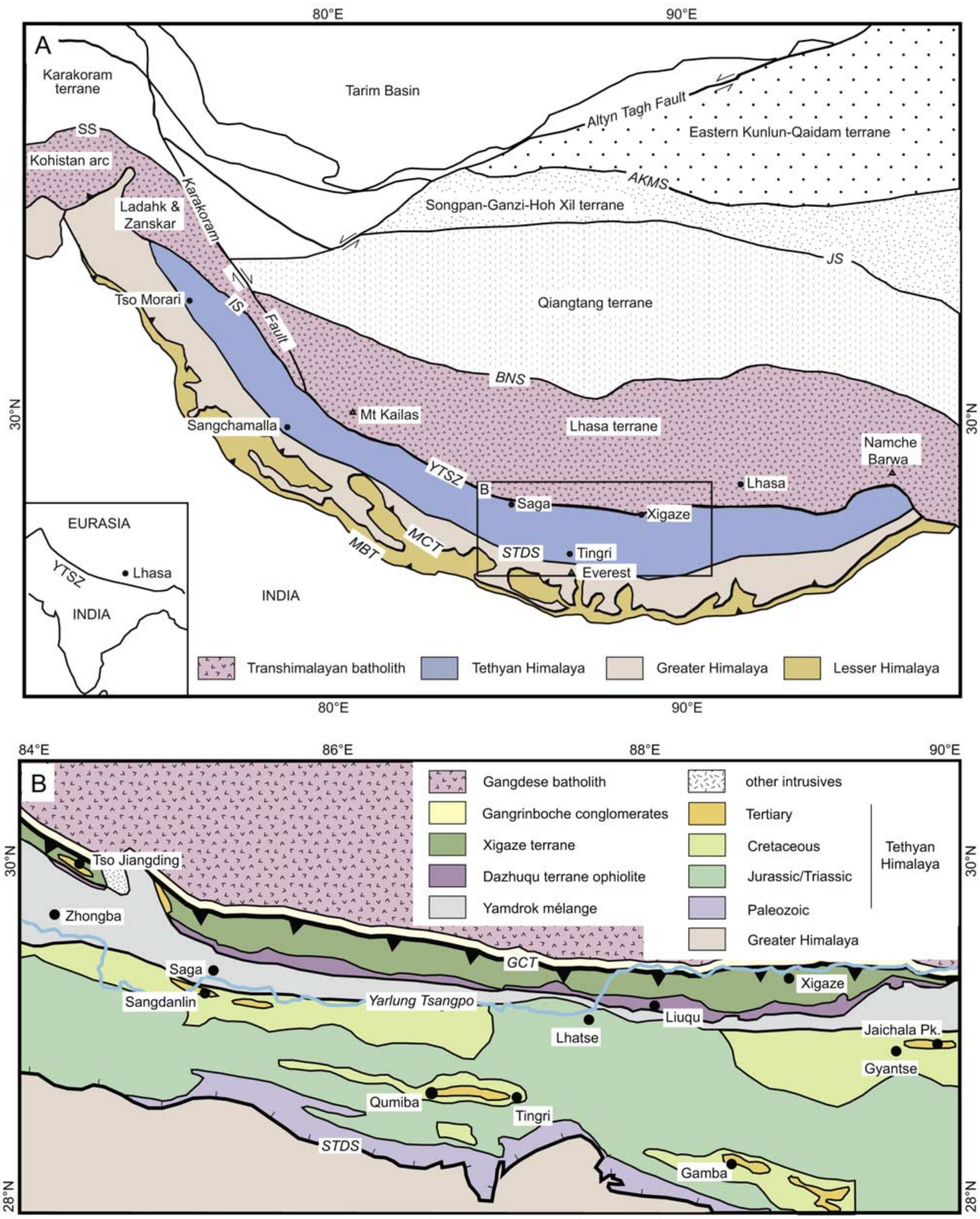

Figure 1

Table 1. Apparent Paleomagnetic Poles for Eurasia at 55 Ma

Study	Longitude, °E	Latitude, °N	α95	Source
Besse and Courtillot [1991, Table 6]	163.5	78.6	4.1[a]	database compilation
Torsvik et al. [2001, Table 1b]	165.8	77.4	2.8	database compilation
Riisager et al. [2002]	154.7	71.4	6.0	Faeroes, new
Besse and Courtillot [2002, Table 4]	177.3	81.2	3.2[a]	database compilation
Ali and Aitchison [2004, Tables 1 and 2]	177.9	72.0	6.8	hybrid
Schettino and Scotese [2005, supplementary Table 7]	179.2	80.3	8.0	database compilation

[a]Poles and associated α95 values are interpolations based on the 60 and 50 Ma values listed in the respective works.

these responses appears to have gone unnoticed. Even global events, rightly or wrongly attributed to collision appear to have lagged ≥20 Ma after the widely accepted time for collision inception.

[7] Over the past two decades, both the abundance and precision of data have improved making it timely to reconsider the constraints geological data place on the most significant tectonic event to have occurred in the past 100 Ma. In this paper, we first consider the relative positions of India and Asia through the early Cenozoic allowing us to constrain when these two continental masses were close enough to make first contact. Their considerable separation at 55 Ma renders any interaction between them highly unlikely. Secondly, by reexamining constraints on events in the geological record cited by earlier workers as their basis for estimating the timing of contact between India and Asia in the light of new data we are able to propose a new model for evolution of the system. Our model not only assumes collision at a much later date (≤35 Ma), it is also able to provide a viable explanation for older geological phenomena. If correct, then models for tectonic and climatic evolution associated with the Himalaya-Tibetan orogenic system, in which a T_0 boundary condition of 50–55 Ma is assumed [e.g., *Beaumont et al.*, 2001, 2004; *Jamieson et al.*, 2004] require critical reassessment.

2. Plate Tectonic Considerations

[8] Clearly, any debate on the timing of the India-Asia collision must be informed by knowledge of the relative positions of the colliding entities at various times. Considerable progress has been made toward establishing: the position of "stable" Eurasia and its motion track; the position of India and its rate of convergence toward Eurasia; and the likely size of "Greater India."

2.1. Position of Eurasia During the Cenozoic

[9] Although Eurasia is one of the largest and slowest moving continental blocks, working out its past position, certainly for the early Cenozoic, is not as simple as is commonly envisaged. As explained by *Ali and Aitchison* [2004], the problem stems from the fact that very few paleomagnetic data are available for the stable part of the plate for the last 100 Ma. Practically all poles are from lower Paleogene rocks (~11 Ma age range) within a geographically restricted area of the plate in the European North Atlantic igneous province (i.e., NW Britain and the Faeroe islands).

[10] Table 1 shows some of the apparent paleomagnetic poles proposed for Eurasia at 55 Ma, the time when India is widely considered to have begun colliding with Asia [*Najman*, 2006]. When "viewed" from southern Tibet, all plot to the right-hand side of the present-day pole, indicating 10 to 21 degrees clockwise motion of the region since the early Eocene. The apparent pole of *Riisager et al.* [2002] requires the largest latitudinal motion (~6° southward) since it plots on the nearside of the North Pole (Figure 2). The preferred pole is a "hybrid" [*Ali and Aitchison*, 2004, 2006], and is based on the *Riisager et al.* [2002] Faeroe Islands pole together with one obtained from lower Eocene sedimentary rocks in southeast England [*Ali et al.*, 2003]. The validity of the proposed pole was then tested using high-quality data from two basalt flow sequences in the Tien Shan range in Kyrgysztan [*Bazhenov and Mikolaichuk*, 2002] and western China [*Huang et al.*, 2005]. This pole, along with those of *Besse and Courtillot* [2002] and *Schettino and Scotese* [2005], requires negligible latitudinal motion of Eurasia since 55 Ma.

[11] Hard quantitative data on the Cenozoic position of the Lhasa block are limited. In fact, the authors are currently undertaking a paleomagnetically focused research program to address this issue. Only the studies by *Achache et al.* [1984] and *Otofuji et al.* [1991] appear reliable, satisfying several of the key acceptance criteria proposed by *Van der Voo* [1990] and being listed on the global paleomagnetic database (http://www.ngu.no/dragon/Palmag/paleomag.htm). Other works have been published [*Westphal et al.*, 1983; *Otofuji et al.*, 1989; *Zhou et al.*, 1990; *Dong et al.*, 1991] but cannot be reliably used for plate modeling. The results from the first study were discarded because only two sites, 3 and 6, yielded clustered characteristic magnetization directions, but the angular separation of the means was 43.4°. The second only lists data from two sites (6, 25) that could be from Cenozoic rocks. The two China-based studies have

Figure 1. (a) Regional map indicating major tectonic units and boundaries within the Tibet-Qinghai Plateau: AKMS, Anyimaqen-Kunlun-Muztagh suture; JS, Jinsha suture; BNS, Bangong-Nujiang suture; SS, Shyok suture; IS, Indus suture; YTSZ, Yarlung Tsangpo suture zone; STDS, South Tibet detachment system; MCT, Main Central thrust; MBT, Main Boundary thrust. (b) Regional geological map of southern Tibet indicating positions of key localities in southern Tibet where critical outcrops provide constraints on the timing of the India-Asia collision. GCT, Great Counter thrust; STDS, South Tibet detachment system. Note that the distribution pattern of some key units with restricted outcrop is slightly exaggerated in order that they are visible on this map.

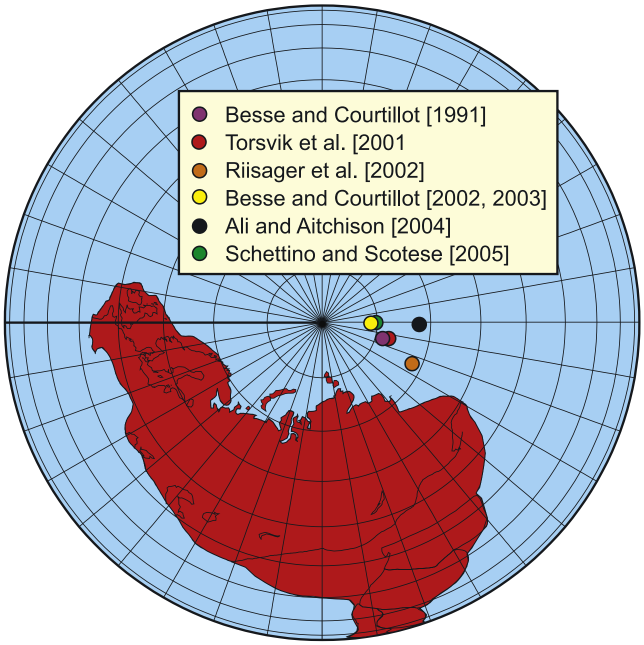

Figure 2. Stable Eurasia with various pole proposals for the block at 55 Ma, see text. The image is based on the Eurasiayoung stencil of the GMAP program [*Torsvik and Smethurst*, 1999] plotted on an orthogonal projection as viewed from above the North Pole. This stencil is modified slightly by extending Tibet south to include all of the ground north of the Yarlung Tsangpo suture. The Greenwich Meridian and 90°E point toward the left-hand side and the bottom, respectively.

limited value for tectonic studies because they used somewhat simple laboratory processing and data analyses.

[12] The work of *Achache et al.* [1984] was in essence a reconnaissance study. They sampled the lower Paleogene Linzhizong Formation at two small geographical areas, one to the north of Lhasa a second to the northwest. Data were presented from seven sites. Of these, six (24–26, 28, 40, 41, and 47) are considered reliable because the site mean $\alpha 95$ values were less than $\leq 13.6°$; the discarded site, 39, has an angle of 21.5°. Eliminating site 47 from the mean calculation, similar to *Achache et al.* [1984], generates a reverse polarity tilt-corrected mean direction of D = 176.5°, I = −28.5°, $\alpha 95$ = 10.2°, k = 44.0, the inclination angle suggesting a formation latitude ~15°N. The study by *Otofuji et al.* [1991] focused on the 42 Ma Quxu pluton, which was sampled at nine sites on the Lhasa-Quxu road ~40 km SW of Lhasa. A single site, WT31, was also sampled from the Linzizhong volcanics. As with many studies of granites, the results were far from perfect almost certainly due to the coarse texture associated with such rocks, and the rather low magnetic intensities: $0.4–1.5 \times 10^{-2}$ mA/m. Only two sites (T28, T29) yielded apparently primary directions, with inclinations of 45.4° and 31.0°, respectively. The single site from the Linzizhong volcanics yielded a normal-polarity-corrected mean inclination of 23.7°.

[13] The summary shows how poor the existing paleomagnetic database is for the Cenozoic rocks of southern Tibet. Also, there are no data from Oligocene–middle Miocene magmatic rocks. Finally, in this section, although geological arguments for the amount of Asia shortening have proposed (several hundred kilometers [e.g., *Johnson*, 2002]), we would argue that many of the underlying assumptions are incorrect. The Gangdese batholith and Linzizhong volcanics are components of the magmatic arc that developed as in response to subduction of Neo-Tethyan oceanic lithosphere beneath the southern margin of Eurasia. Therefore they must have formed within a few hundred km of the associated trench and can be used to define its position.

2.2. Size of India Prior to Its Collision With Eurasia

[14] The extent to which the continental crust existed, in the form of a Greater India, beyond the present-day northern limit of the Indian craton has been the subject of intense speculation. A major review of the issue was recently published by *Ali and Aitchison* [2005]. Aside from discussing over thirty key proposals, the earliest dating from the 1920s, a new model accommodating an extension to the north of the craton was presented based on the refitting of the subcontinent back into Gondwana together with bathymetric information from the SE Indian Ocean (Figure 3). Greater India's northern limit was fixed using the Wallaby-Zenith fracture zone offshore of western Australia. The maximum possible extension, ~950 km, was northeast of the central part of the craton, presently 80–84°E. North of the eastern and western syntaxes, the proposed extensions were ~500 and 600 km, respectively. *Ali and Aitchison* [2005] also noted that as India rotated counterclockwise away from Australia, the Wallaby-Zenith fracture zone boundary was a right-lateral transform fault. Therefore the ocean-continent transition north of the Greater India would very likely have been very sharp, possible just 5–10 km wide as is the case for the Romanché fracture zone south of Ghana [*Edwards et al.*, 1997; *Mascle et al.*, 1997]. Critically it would not have been thinned and extended as, for example, is the case off western Iberia in the North Atlantic [*Whitmarsh et al.*, 2001].

2.3. Motion History of India

[15] There have been numerous attempts to describe the Indian continent's motion during the Late Cretaceous and Cenozoic [e.g., *Blow and Hamilton*, 1975; *Klootwijk et al.*, 1991; *Patriat and Achache*, 1984]. Four of the more detailed studies published over the last decade and a half [*Acton*, 1999; *Besse and Courtillot*, 1991, 2002; *Schettino and Scotese*, 2005] are summarized in Figure 4. All show the central part of the Indian craton 30–35°S in the Late Cretaceous at 80 Ma. In all models, the positions of the subcontinent at 80, 60, 40, 20, and 0 Ma are broadly similar, particularly in the three most recent works. *Acton*'s [1999] path is preferred because it is based on several forms of paleomagnetic data and makes use of the alignment and specific age points along both the Reunion–Deccan Trap and Kerguelen–Ninety East Ridge hot spot tracks. The exhaustive review and synthesis refines considerably previous estimates of the craton's motion north toward Asia. It uses data from the Indian continent and deep marine sequences in the Indian Ocean, as was the case with earlier studies [e.g., *Klootwijk et al.*, 1991]. In addition, 19 Late

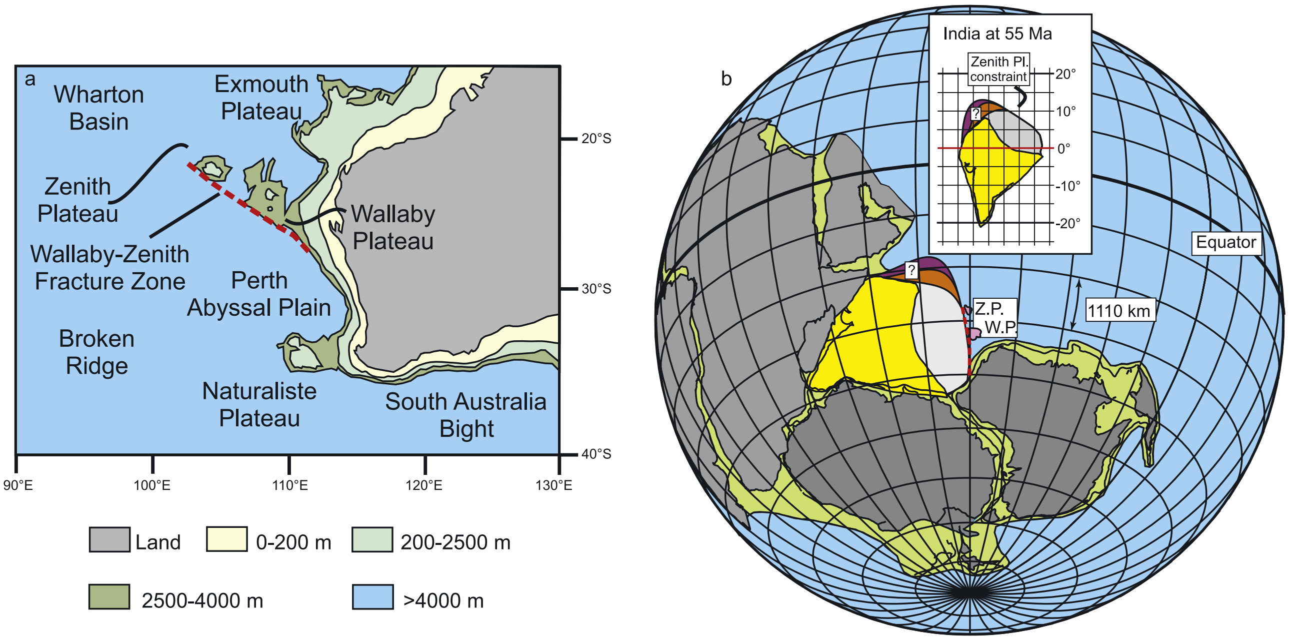

Figure 3. (a) Simplified bathymetric chart of the southeast Indian Ocean (Mercator projection) based on GEBCO atlas from the *Intergovernmental Oceanographic Commission et al.* [2003]. Note the Wallaby–Zenith Plateau Ridge extending W-NW from western Australia. The Wallaby and Zenith plateaus are blocks of thinned continental crust [*Brown et al.*, 2003; *Symonds et al.*, 1998], and the Wallaby–Zenith Fracture Zone is shown by the dashed red line. South of the fracture zone, the oldest ocean floor in the Perth Abyssal Plain is ~131 Ma (M11 age). (b) Gondwana in the Middle Jurassic (~160 Ma) drawn using the GMAP program [*Torsvik and Smethurst*, 1999]. Note the Wallaby and Zenith plateaus (Z.P. and W.P.) and the Wallaby–Zenith Fracture Zone (dashed red line). Also shown is the proposed Greater India extension at this time and at 55 Ma based on *Acton*'s [1999] pole.

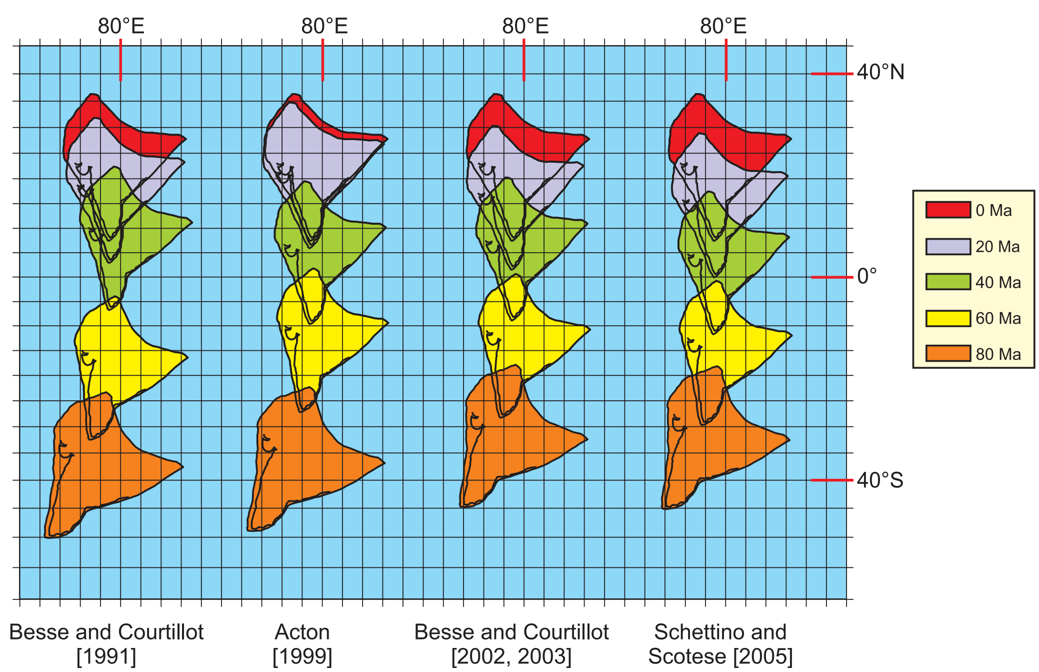

Figure 4. Summary of some recent India craton motion path (80–0 Ma) proposals [*Acton*, 1999; *Besse and Courtillot*, 1991, 2002; *Schettino and Scotese*, 2005] plotted on a Gall's-type cylindrical projection. The 80°E longitude line is highlighted in each model. Latitudes and longitudes are at 5° intervals.

Cretaceous to end Oligocene poles from other continents are rotated into an India reference frame via an ocean floor spreading history model tied to a series of fixed/slow moving hot spot tracks were used to position the subcontinent at different times.

[16] The rate of India's northward progression toward Asia was ~6.6 cm/yr between 120 and 73 Ma, increasing to ~21.1 cm/yr between 73 and 57 Ma. At 57 ±3 Ma, there was then an abrupt and massive slowdown (to 9.5 cm/yr) until 20–30 Ma, when there was a further major slowdown. At this juncture we quote *Acton* [1999, p. 163] directly: "Interestingly, India's rate of northward motion, while being much slower after 57 Ma, was still quite rapid until about 20–30 Ma. Whatever happened at 57 Ma, India's journey northward was far from over." Note with the scheme of *Acton* [1999] that in the 10 Ma interval straddling the Paleocene/Eocene boundary, India is farther north than in the other models (Figure 4). As a consequence, the chance of India-Asia collision to take place in this time window is maximized.

2.4. Plate Tectonic Model

[17] From a purely plate tectonic perspective, with the key elements of the India-Asia convergence system apparently fixed, establishing the location and timing of collision should be straightforward. Figure 5 shows the India and Asia at 70 Ma (oldest proposed collision time) and 55 Ma (widely assumed collision time). Contact of India with Tibet at 55 Ma, or indeed anytime before, would appear physically impossible as the two margins of the blocks involved in the orogeny were nowhere near one another at that time. Proposals for collision taking place in the Late Cretaceous, 65–70 Ma [e.g., *Ding et al.*, 2005; *Klootwijk et al.*, 1991; *Yin and Harrison*, 2000] are more problematic. Although it has been proposed that terrestrial vertebrate fossils indicate continuity had been established between India and Asia prior to 65 Ma [*Jaeger et al.*, 1989; *Rage et al.*, 1995] a connection with southern Tibet is implausible. An alternative suggestion would be to look at possible contacts with nearby SE Asia at that time. If the basic plate model is correct (Animation 1), and there is no evidence to suggest otherwise, the event must be of latest Eocene or younger age (≤35 Ma).

3. When Did the India-Asia Collision Occur: The Rock Record?

[18] Since the early 1980s, the paradigm for the India-Asia collision has been based on the hypothesis that the Tethyan oceanic lithosphere was consumed along a single zone of plate convergence located at the southern margin of Eurasia, with continent-continent collision occurring around the Paleocene/Eocene boundary [*Harrison et al.*, 1992; *Klootwijk et al.*, 1992b; *Molnar and Tapponnier*, 1975; *Molnar et al.*, 1993; *Patriat and Achache*, 1984; *Searle et al.*, 1987]. However, more recent research along the Yarlung Tsangpo suture zone (YTSZ) in Tibet has led to significant advances in our understanding of the nature of the Neo-Tethyan ocean floor and tectonic elements within it providing a basis for predictions about the nature of events that should be recorded along the suture zone.

[19] At the time of Sino-French and Sino-British collaborative programs (early 1980s), when modern tectonic investigations began along the Yarlung Tsangpo suture zone, it was a widely believed that ophiolites represented remnants of mid-ocean ridge material and their presence on land is indication of an ocean closure. It is now apparent that Neo-Tethys was like large oceans present today in which intraoceanic island arcs, plateaus, seamounts and other bathymetrically positive features exist. Largely as a result of subsequent Ocean Drilling Program investigations, we now know that many ophiolites form in suprasubduction zone (SSZ) settings associated with intraoceanic island arcs. As such they lie in an upper plate tectonic position that favors their obduction during arc-continent collision whereas true mid-ocean ridge material on the lower plate is preferentially subducted. Turbidites of the Xigaze Group were originally interpreted as the fore arc of a continental margin subduction system, which developed along the southern margin of Eurasia [*Einsele et al.*, 1994; *Girardeau et al.*, 1984; *Marcoux et al.*, 1982; *Nicolas et al.*, 1981]. Recent work, however, has demonstrated that Dazhuqu terrane ophiolites near Xigaze are not basement to a continental margin fore arc but represent a discretely different intraoceanic terrane that formed at equatorial latitudes [*Abrajevitch et al.*, 2005; *Aitchison et al.*, 2000, 2002b, 2004]. Similar SSZ ophiolitic rocks occur as klippe thrust southward over Tethyan Himalayan rocks along the length of the Indus-Yarlung Tsangpo suture zone (e.g., Pakistan [*Beck et al.*, 1995] NW India (Spongtang and Nidar ophiolites [*Corfield et al.*, 2001; *Ahmad et al.*, 2005]), western Tibet (Yungbwa ophiolite [*Miller et al.*, 2003]), Xigaze region (Dazhuqu terrane [*Aitchison et al.*, 2004]) etc.). Their obduction records the demise of the intraoceanic system rather than the closure of Neo-Tethys. Evidence of the collision of this intraoceanic island arc with the northern margin of India should be present in the sedimentary record (and is discussed later in section 4). Neo-Tethys was obviously more complex than originally envisaged as another intraoceanic island arc system, remnants of which are represented by the Kohistan-Dras arc, collided to the north with Eurasia well before the ocean closed.

3.1. Final Marine Deposition Between India and Asia

[20] The subsidence record from the youngest reported marine rocks in the Tethyan Himalayan marine succession immediately south of the suture zone, provides an important constraint on the initiation of collision, with the youngest marine strata placing a key maximum age limit [*Rowley*, 1996]. The relevant outcrops best known in the international literature lie to the north of Mt Everest (Qomolangma) in the Zhepure Shan, between Qumiba and Tingri (Figures 1a and 6d). *Wang et al.* [2002] reported a previously undescribed section from this mountain range near Qumiba containing marine sediments the uppermost of which preserve an end Eocene (Priabonian ~35 Ma) NP20 nannofossil assemblage. Although this finding is disputed by *Zhu et al.* [2005], we see no basis for their rejection of this work, and it has been confirmed by several other Chinese studies [*Li and Wan*, 2003; *Li et al.*, 2000; 2002; *Xu*, 2000]. Problems certainly exist with the accuracy of coordinates given for the location (the actual location measured by Garmin 76C GPS using the WGS84 map

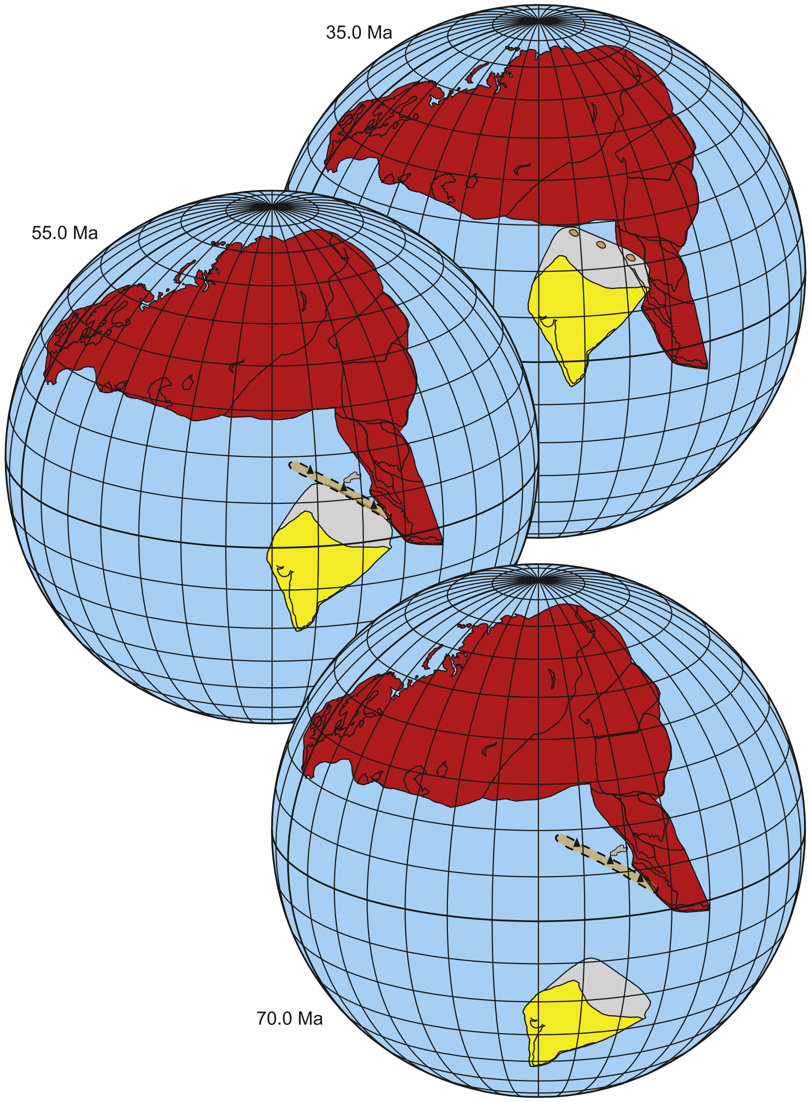

Figure 5. India and Eurasia at 70, 55, and 35 Ma drawn using the GMAP software [*Torsvik and Smethurst*, 1999] plotted on orthogonal projections (viewed from 70°E, 20°N). India's positions are based on the work by *Acton* [1999]; extension to the India craton is from *Ali and Aitchison* [2005]; positions of Asia are based on the work by *Ali and Aitchison* [2004, 2006] and assume steady state motion between 70 Ma and the present (see text; the Eurasiayoung stencil is modified as for Figure 2). As the detrital sedimentary record indicates, collision of India with an intraoceanic island arc at ~55 Ma, a likely position for this arc (brown zone marked by volcano symbols), can also be shown. On all three images the stencils for Indochina and western Sundaland have been modified following *Hall* [2002]: relative to Eurasia, Indochina has been rotated counterclockwise to accommodate ''extrusion,'' while south and west Sundaland has been rotated counterclockwise relative to the Malay peninsular. Eastern Sundaland (principally Borneo) is not shown.

datum is 28°41.245′N/086°43.968′E). However, having sought additional clarification from the Wang et al., we visited the locality in June 2006 and resampled for additional analysis of the nannofossil assemblages present. Preliminary investigations (J. Firth, IODP Supervisor of the Micropaleontological Reference Center at TAMU, personal communications, 2006, 2007) confirm the findings in the original work of *Wang et al.* [2002]. *Zhu et al.* [2005] queried the validity of the original nannofossil study because *Wang et al.* [2002] also reported reworked Mesozoic forms in their samples. *Zhu et al.* [2005] further seem to imply that the NP20 assemblage may also be reworked. However, there is no evidence for this and even if there were the sample must still indicate that marine conditions prevailed in the area between India and Asia until the end of the Eocene. Interestingly, the section studied in detail and reported on by *Zhu et al.* [2005] lies very close to that studied by *Wang et al.* [2002], being immediately west of a drainage divide and containing essentially the same stratigraphic succession. In fact, in 2006 we traced the stratigraphy from one section to the other without difficulty. Although *Zhu et al.* [2005] did not report any nannofossil

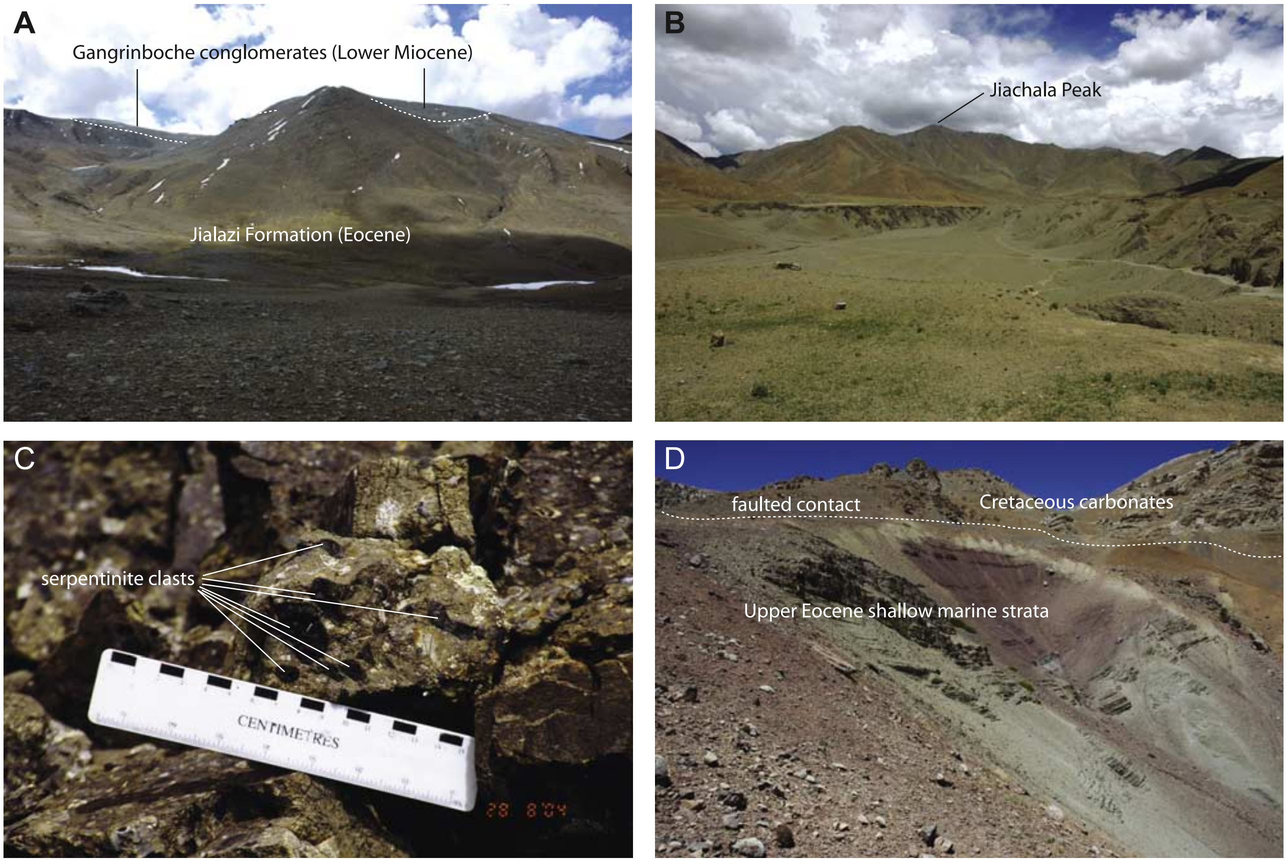

Figure 6. Photographs from key localities in southern Tibet that provide important constraints on the timing of collision events during the subduction then closure of Tethys. (a) Fore-arc basin deposits of the Xigaze terrane at Tso Jiangding (29°56.970′N/084°20.785′E) NE of Zongba. These are overlain with angular unconformity by fossiliferous Eocene shallow marine sediments (sunlit area in foreground) that are overlain, in turn, with angular unconformity by upper Oligocene–lower Miocene Gangrinboche conglomerates (top of peak) (photograph viewed looking to the east). (b) Marine dinoflagellate-bearing coarse-grained sedimentary rocks exposed atop Jiachala Peak (~5445m, 28°55.393′N/089°50.313′E) located to the NE of Gyantse. These rocks indicate the persistence of marine conditions into the early Eocene (photograph viewed looking to the east). (c) First conglomerates to contain evidence of the collision of an intraoceanic island arc with India. These conglomerates are preserved in sections at Sangdanlin (29°15.373′N/85°14.994′E), immediately south of the suture near Saga. The dark clasts are ophiolite-derived serpentinite. (d) Photograph, viewed looking to the north, of the section (28°41.245′N/086°43.968′E) reported by *Wang et al.* [2002] of marine sedimentary rocks near Qumiba that contain an upper Eocene (upper Priabonian ~35 Ma) nannofossil assemblage.

investigations the samples we collected from their section appear to be of the same age as those in the *Wang et al.* [2002] section.

[21] *Wang et al.* [2002] assigned the rocks described from their section to a new unit, the "Pengqu Formation." They discriminated two members within this formation. The lower one, Enba member, characterized by green colored lithologies and the upper unit, Zhaguo member, dominated by red sediments. They noted an erosional surface representing a brief hiatus of less than one nannozone between these two units. We are not in agreement with *Zhu et al.* [2005], who reject this stratigraphic nomenclature and claim the existence of a major disconformity. First our observation of the section in question and nannofossil samples indicate the conclusions of *Wang et al.* [2002] regarding the duration of the sedimentary hiatus are correct. Although the presence of the disconformity suggests that the two members are best regarded as separate formations rather than members of a single formation, we see no reason to disregard the priority of the names introduced by *Wang et al.* [2002]. Differences over stratigraphic nomenclature notwithstanding, the actual timing for the cessation of marine sedimentation at Qumiba remains a minimum estimate (NP20), as the reported section is incomplete with deposits younger than 35 Ma having been eroded. It remains to be determined whether marine sedimentation had ceased by then or if it continued for some time prior to the initiation of continental molasse accumulation.

[22] In his review of literature pertaining to the age of the initial India and Asia contact, *Rowley* [1996, p. 1] stated "In the most eastern section of Tertiary rocks thus far recognized within the Tethyan Himalaya 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 the collision) must be still younger.'' Later, *Rowley* [1998] followed this line of reasoning to infer marked diachroneity along the suture, with the initial collision regarding as having occurred farther to the west in the Zanskar region dated at 50.7 Ma. This was based on a change in sedimentation from shelf sediments of the lower Ypresian Patala Formation to turbidites of the Balakot Formation, which at that time was regarded as an upper Ypresian to lower Lutetian unit [*Bossart and Ottiger*, 1989]. The issue appeared to be resolved when the presence of SSZ-ophiolite-derived detrital Cr-rich spinel grains in sandstones of the Youxia and Shenkeza formations (equivalent to Enba and Zhaguo members, respectively, of the Pengqu Formation of *Wang et al.* [2002]) in the Qumiba section was reported [*Zhu et al.*, 2005]. These Cr-rich spinels were interpreted to indicate the onset of India-Asia collision in southern Tibet at 50.6 ± 0.2 Ma thereby eliminating the perceived problem of a diachronous collision [*Rowley and Currie*, 2006; *Zhu et al.*, 2005]. Strangely, this is at odds with previous assertions that the youngest marine strata should indicate the maximum age for collision given that numerous Chinese workers had published reports of late Eocene nannofossil assemblages from this section [*Li and Wan*, 2003; *Li et al.*, 2000, 2002; *Wang et al.*, 2002; *Xu*, 2000] as the implication is that marine sedimentation continued along the axis of the collision for >17 Ma following its initiation. We note that if India were moving at 5 cm/yr toward Asia, then it would have migrated 850 km in 17 Ma; the Straits of Taiwan, which separate the province of Taiwan from the Chinese mainland, lie in an equivalent tectonic position in the present-day collision between the Luzon arc and the Eurasian continent. The zone of marine sedimentation is much less than 850 km in width as the distance across the straits is <150 km. We also note that an alternative explanation to the issue of apparent diachroneity may have already been provided as more recent investigations of the Balakot Formation have shown that it is structurally intercalated with older rocks and must have been deposited after the metamorphism, uplift and erosion of 37 Ma micas that constitute part of the detrital content of this unit [*Najman et al.*, 2001, 2002]. (We comment further on the significance of detrital Cr-rich spinel in the Paleocene–early Eocene sediments at Qumiba and elsewhere in section 4.)

[23] Other recent work in other parts of the Tethyan Himalayan succession by Chinese investigators has resulted in additional reports of Eocene marine sediments, suggesting they may be considerably more widespread than commonly thought. To the east, near Gyantse, marine dinoflagellates indicate the persistence of marine conditions into the early Eocene (the locality is on Jiachala Peak (~5445 m, 28°55.393′N/089°50.313′E, Figures 1b and 6b) [*G. B. Li et al.*, 2005]) and radiolarians in nearby siliceous sediments record deep marine sedimentation until at least the Paleocene/Eocene boundary [*Liu and Aitchison*, 2002]. Farther to the west at Sangdanlin (29°15.373′N 85°14.994′E), immediately south of the suture near Saga, the presence of radiolarians as young as mid-Eocene has been reported [*Fang et al.*, 2006, p. 63]. In a part of western Tibet dinoflagellates, pollen and radiolarians as young as middle Eocene have been reported from the upper levels of the Sangchamalla Formation [*Mehrotra and Sinha*, 1978, 1981; *Sinha*, 1989]. We note that this finding is contested [*Jain and Garg*, 1986; *Juyal et al.*, 2002], however, geopolitical disputes between India and China make it difficult to visit the locality (Sangchamalla approx 30°47′N/80°11′E, Figure 1a) in order to verify this. Elsewhere throughout the Tethyan Himalayan zone sections are either, less complete, or less well studied, with the youngest marine sediments reported commonly being nummulitic limestones containing a Ypresian (P8) foraminiferal assemblage (the significance of this is discussed in section 4). At all reported localities sections are erosionally truncated, thus foraminiferal assemblages merely indicate when marine conditions prevailed rather than when they terminated.

[24] It is possible to present a case that tectonic loading depressed the Tethyan Himalayan zone at the leading edge of the underriding plate during the inception of collision and suggest therefore that the youngest marine sediments do not necessarily reflect the timing of collision. However, it is difficult to envisage a scenario involving similar tectonic loading of the overriding plate (Lhasa block) in this system. The presence of an Eocene marine sedimentary section on the northern side of the Yarlung Tsangpo suture zone overlying, with angular unconformity, fore-arc basin deposits of the Xigaze terrane at Tso Jiangding (alternative transliterated as Cuojiangding by *Rowley* [1996]) (29°56.970′N/084°20.785′E,) NE of Zongba is reported in the Chinese literature [*Liu et al.*, 1988]. More recently, *Ding et al.* [2005] reported a P9 foraminiferal assemblage in this section from immediately below the angular unconformity above which lie the upper Oligocene–lower Miocene Gangrinboche conglomerates (Figure 6a). Having visited the area in 2006, we can confirm the existence of this section of shallow marine sedimentary rocks rich in foraminifera and nannofossils. Although the section preserved in the core of a syncline is erosionally truncated, it is entirely marine, and the uppermost beds contain an early/middle Eocene boundary fauna, indicating that marine deposition on the Asian side of the collision continued until at least 49 Ma. Elsewhere on the Lhasa block Eocene basins exhibit the type of sedimentation that might be expected along an Andean-style convergent margin, and predate the collision.

3.2. Beginning of Continental Molasse Sedimentation Along the Suture Zone

[25] Detrital sedimentary records along convergent plate margins are widely regarded as key repositories, for precisely constraining the timing of both major and minor tectonic events [*Lundberg and Dorsey*, 1990]. Distinctive orogen-derived detrital deposits (molasse) commonly mark major collision events. Although the signatures of small events can be subtle, they are nevertheless often recorded. Such sedimentary packages occur both within the YTSZ and in the Himalayan foreland, with the development of molasse along the suture clearly linked to collision. We believe that misconceptions over the age of these sediments as well as imprecise age correlations for similar looking deposits along the suture zone [*Searle et al.*, 1987] have been a major contributing factor in the misinterpretation of the timing of the India-Asia collision. Recent investigations permit the discrim-

ination of various conglomeratic units clearly attributable to different tectonic events [*Davis et al.*, 2004].

[26] The oldest sediments that contain detritus from both India and Eurasia (Lhasa block) i.e., either side of the suture, are the upper Oligocene–lower Miocene Gangrinboche facies conglomerates. Although the N-S extent of their outcrop is restricted to the northern margin of the suture zone, these rocks are regionally extensive forming a succession that straddles the length of the suture from east to west [*Aitchison et al.*, 2002a]. They incorporate several locally named units including the Kailas, Qiuwu, Dazhuqu, and Luobusa formations, all of which record similar histories. A similar evolutionary pattern for detrital clasts occurs along the entire strike of the suture (2100 km). The lowermost sediments in each unit were derived from north of the suture and accumulated upon an unconformity surface eroded onto Lhasa terrane basement rocks. Farther up section, the first clasts of Tethyan and Indian affinity herald the onset of collision-related orogenesis south of the suture zone. These clast types subsequently became the dominant detrital components. Their age thus clearly places an upper bound on the timing of collision. Although these rocks were previously reported as Eocene [*Searle et al.*, 1987], stratigraphic relationships indicate that they are in fact upper Oligocene to lower Miocene [*Aitchison et al.*, 2002a]. This is confirmed with new radiometric age determinations from tuffs interbedded with the conglomerates at Mt Kailas and Dazhuqu, which yield Ar-Ar ages of 16.9 ± 0.2 Ma and 20.1 ± 0.5 Ma, respectively (J. C. Aitchison et al., submitted to *Earth and Planetary Science Letters*, 2007).

[27] Correlative sediments from within the suture zone in NW India are known as the Indus/Ladakh Molasse [*Garzanti and Van Haver*, 1988]. Until recently, biostratigraphic control for this unit was also poor and the only constraint was that they were locally deposited upon an unconformity eroded into lower Eocene carbonates [*Searle et al.*, 1990]. New paleontological studies now indicate that this unconformity represents a considerably greater lacuna than previously envisaged, as a well-preserved upper Oligocene ostracod fauna has been reported [*Bajpai et al.*, 2004] from the Basgo Formation, the basal unit of the Indus Molasse [*Garzanti and Van Haver*, 1988] in outcrops located W-NW of Leh in Ladakh. This discovery is of major significance as the upper Oligocene Basgo Formation is succeeded by the Choksti Formation, the first unit to onlap either side of the Indus suture. It contains material derived from both north and south of the suture thereby providing a major constraint on final closure of Tethys [*Searle et al.*, 1990]. *Clift et al.* [2002] disputed this and claimed that older rocks of the Chogdo Formation occur either side of the suture although this relationship is not well documented, nor is it apparent from their map. Paleocurrent measurements indicate southwesterly derivation from the direction of India with clasts dominated by ophiolitic detritus and red chert [*Clift et al.*, 2002]. Interestingly, as described, the rocks in question appear to bear a strong resemblance to the Liuqu conglomerates of Tibet [*Davis et al.*, 2002] (see further discussion of conglomerates in section 4).

3.3. Regional Sedimentation Patterns

[28] Sedimentation in basins peripheral to the Tibet-Himalayan Plateau region has also been used to further assess the timing of collision. In most cases the data are consistent with a latest Eocene-Oligocene onset to this event. *Yin* [2006] regarded the presence of a major regional (“basin-wide” [*Najman*, 2006]) unconformity marked by the absence of latest Eocene–Oligocene sedimentary rocks as “an interesting observation.” Several potential explanations were proposed, yet remarkably the obvious relationship of this unconformity to collision appears to have been overlooked. We can only surmise that this is simply because the 55 Ma collision dogma so deeply permeates interpretation that the likelihood this unconformity records the timing of collision initiation is not even considered. *DeCelles et al.* [1998a] link development of the unconformity to propagation of a forebulge south of the growing Tibet-Himalayan orogenic zone well after the initiation of collision. Elements of this interpretation may have validity, especially those pertaining to interpretation of Miocene molasse south of the Himalaya as fore-deep deposits. However, we suggest that the significance of sedimentary rocks below the unconformity and their detrital content may have been misinterpreted (see section 4). Furthermore, problems exist with the suggestion (implicit in the work by *DeCelles et al.* [1998a]) that the location of the forebulge essentially remained static as it should have migrated through the area. If estimates of the rate of India’s northern motion at the time in question [*Acton*, 1999] are correct, then over 16.5 Ma the forebulge would have migrated ~1550 km southward rather than remaining in the same place.

[29] Collisional molasse deposits dominate the fore deep that developed south of the Himalaya. Fluvial sedimentation in the Himalayan foreland did not begin until the Oligocene [*Najman et al.*, 2004]. The Murree Formation in Pakistan is the first unit above the regional unconformity and contains a significant influx of metamorphic detritus [*Critelli and Garzanti*, 1994]. This unit is correlative with the upper Oligocene Dagshai Formation in northern India, the upper levels of which record the first appearance of Himalayan metamorphic detritus [*Najman and Garzanti*, 2000]. The Balakot Formation (section 3.1) is now regarded as the northern correlative of the Dagshai Formation [*Najman*, 2006; *Najman et al.*, 2002]. In Nepal the metamorphic detritus-bearing Dumri Formation overlies the regional unconformity [*DeCelles et al.*, 1998b]. The first major influx of coarse-grained orogen-derived sediment being shed into the fore-deep migrating southward from the developing collision zone is recorded in the overlying Miocene Siwalik Group [*Burbank et al.*, 1996], a unit that is correlated across the Himalayan foreland. Up-section evolution of the Siwalik Group through the Miocene and Pliocene reflects the development of major thrust systems within the Himalaya and the exposure of progressively deeper crustal levels along these faults. In contrast, Eocene through mid-Oligocene sediments in this area, where preserved, are mostly carbonates and reflect tectonic quiescence.

[30] In a regional synthesis of Cenozoic mass accumulation rates in Asia, *Métivier et al.* [1999; p. 315] noted “This mass budget shows that sedimentation in Asia started to rise rather late in the Cenozoic (after 37 Ma), whereas one would have expected it to start at the onset of the India Asia collision.” In more distal basins developed around the periphery of the Himalaya-Tibetan orogenic system, no

appreciable detrital sediment flux occurs until after the mid-Oligocene, when sedimentation rates increased markedly [*Métivier et al.*, 1999].

3.4. Cessation of Continental Subduction Along the Southern Margin of Eurasia

[31] Inherent difficulties in the production of a subduction-related melt from refractory, dry quartzo-feldspathic continental lithosphere [*Ernst*, 1999; *Menzies*, 1990; *Tatsumi and Eggins*, 1995] suggest that volcanism would have ceased shortly after it entered the trench immediately south of the Lhasa block. The depths at which dehydration reactions yield a flux into the overlying mantle wedge and generate calc-alkaline melts are reached by subducting lithosphere within as little as a million years. Thus radiometric age dating of calc-alkaline subduction-related volcanic rocks along the southern margin of Eurasia in the Lhasa block should provide further controls on the initiation of the India-Asia collision. Previously, a lack of data indicating subduction-related magmatic activity in the Lhasa block younger than Paleocene was cited as evidence for an early contact [*Searle et al.*, 1987]. However, an increasing number of igneous rocks from within the Lhasa block, with clear subduction-related calc-alkaline affinities, have now been dated [*Chung et al.*, 2005; *Miller et al.*, 2000]. They indicate that the production of voluminous Andean-style intrusions and volcanic rocks along Eurasia's southern margin continued until at least 37 Ma. Although younger volcanic rocks also occur on the Tibetan Plateau they typically have shoshonitic affinities, and are regarded as postcollisional [*Chung et al.*, 2005].

3.5. Initiation of the Major Collision-Related Thrust Systems in the Himalayan Ranges

[32] Thrust faulting and major uplift is, without exception, a typical, immediate, and strikingly obvious manifestation of all active collisions on Earth today. For instance active collisions in Taiwan [*Huang et al.*, 2000], the Banda arc east of Timor [*Richardson and Blundell*, 1996], central Japan [*Niitsuma*, 1999], and Papua New Guinea [*Hill and Raza*, 1999] have all resulted in thrust faulting and orogenesis with development of juvenile topographic relief of $\geq$4000 m. In all cases, a geologically immediate response accompanies entry of continental lithosphere into the subduction system, and is marked by uplift and the production of orogen-derived detrital sediments. The initiation of significant uplift in Tibet [*Harrison et al.*, 1992] is consistent with a model in which continental collision began during the Oligocene. The oldest dated structures associated with the Main Central thrust system are amphibolite-facies shear zones, which developed 23–20 Ma [*Hodges*, 2000]. Additional displacement occurred along major structures within the Himalayan zone such as the Main Boundary and Main Frontal thrusts, and these south directed systems became progressively younger southward across the Himalaya. The structures and their southward age progression are what might be expected of a collision system, with thrusting likely to have begun at the inception of the collision. Paleocene–early Eocene regional crustal shortening and attendant "Eohimalayan" metamorphism is also recorded in the Tethyan Himalaya [*Burg*, 1992; *Burg and Chen*, 1984; *Burg et al.*, 1987; *Ratschbacher et al.*, 1994; *Wiesmayr and Grasemann*, 2002] but, when considered in the light of other stratigraphic constraints, is best interpreted as being related to earlier arc-continent collision (see section 4).

3.6. Summary

[33] Over the past two decades new data have shown that the youngest marine sediments, the first appearance of molasse derived from either side of the YTSZ, the latest subduction-related volcanics and the development of associated collision-related thrust systems across southern Tibet and the Himalaya are all considerably younger than previously estimated. If the original arguments [*Searle et al.*, 1988] that these phenomena provide primary lines of evidence with which to constrain the timing of the India-Asia collision remain valid, then this suggests that continental collision must have occurred appreciably later than previously thought. Numerous other important tectonic events attributable to the collision, such as "Neohimalayan" metamorphism, also began at $\leq$35 Ma (Figure 7). Widespread collision-related crustal melting, giving rise to generation of the High Himalayan Crystalline Series leucogranites, still did not begin until the early to mid Miocene and was then followed by the development of the northern Himalayan Gneiss domes [*Hodges*, 2000].

[34] A widely discussed model for the likely tectonic response to the India-Asia collision is that of extrusion tectonics [*Tapponnier et al.*, 1982]. We note that features ascribed to this phenomenon are Oligocene to Miocene and younger. For example, the left-lateral slip on the Red River Fault began during the early Oligocene [*Leloup et al.*, 1995, 2001], at a similar time to the commencement of seafloor spreading in the South China Sea [*Q. Li et al.*, 2005]. If, as has been argued, these phenomena were related to the collision, it is difficult to understand why such responses, which are specifically considered to involve rigid blocks should have lagged >20 Ma behind the event.

[35] The India-Asia collision is of global significance and widely regarded as being implicated in the late Cenozoic initiation of global climate change. It has been argued that the shift in ocean geochemistry (e.g., the ∂^{18}O and Sr isotope records) implicated in global climate change can be connected with the India-Asia collision [*Raymo and Ruddiman*, 1992; *Ruddiman and Kutzbach*, 1989]. If so, initiation of this process correlates considerably better with an Oligocene rather than a Paleocene collision-related uplift of the Tibetan Plateau. Recent paleobotanical studies from China also indicate changes in regional climate around the end of the Oligocene with the transition to an East Asian monsoon system [*Sun and Wang*, 2005].

4. What Happened Around 55 Ma?

[36] If, as the geological record and constraints on the relative positions of India and Asia demand, the continental collision occurred no earlier than the Oligocene, it is necessary to account for the ~55 Ma event(s) recorded in the Tibet-Himalayan region. Examination of modern ocean basins [*Intergovernmental Oceanographic Commission et al.*, 2003] suggests that it is highly unlikely that Tethys was a featureless ocean basin. Any features such as intraoceanic arcs, oceanic plateaus or seamounts that once existed within

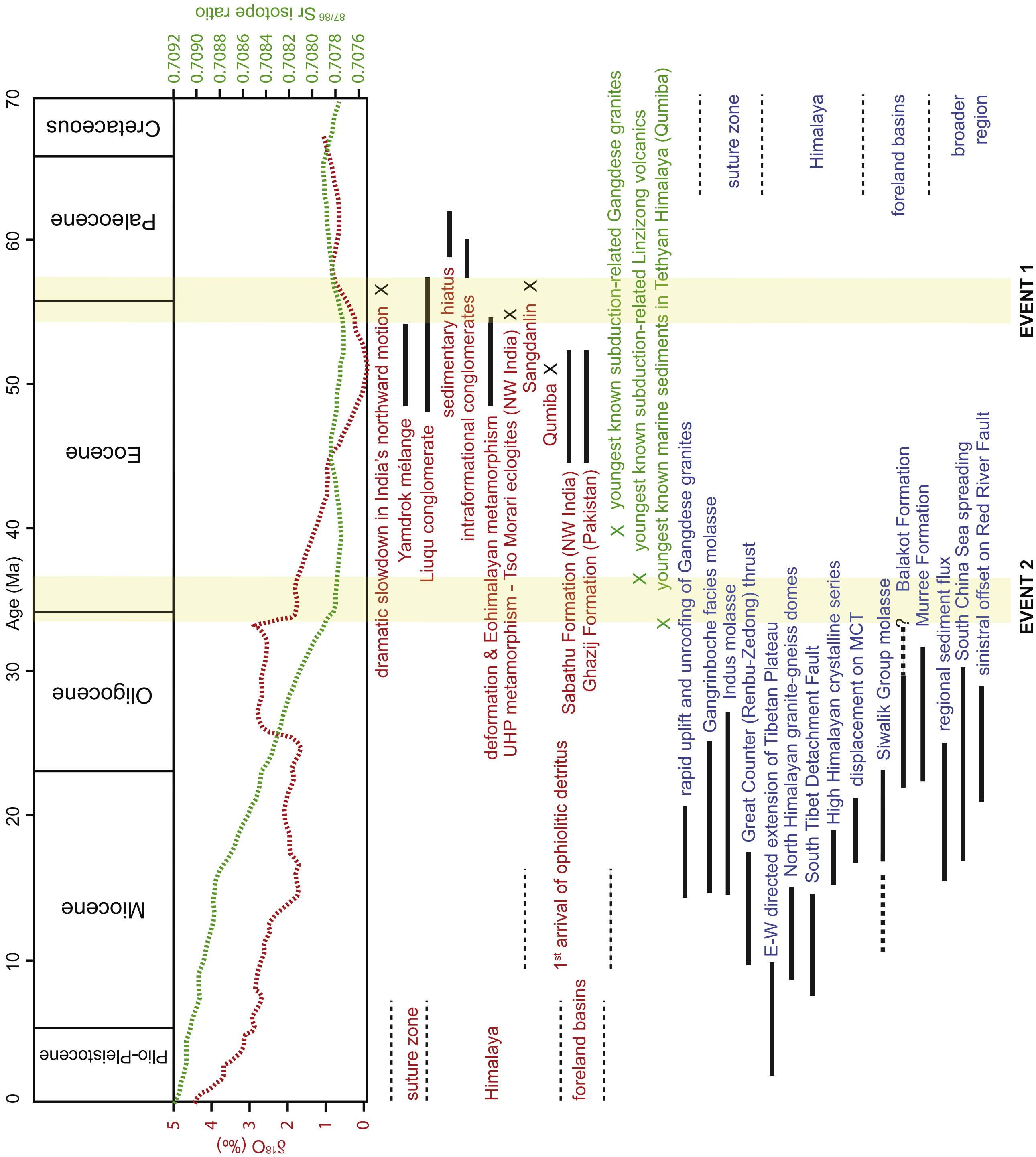
Age (Ma)
0
10
20
30
40
50
60
70
Plio-Pleistocene
Miocene
Oligocene
Eocene
Paleocene
Cretaceous
δ18O (‰)
5
4
3
2
1
0
87/86 Sr isotope ratio
0.7092
0.7090
0.7088
0.7086
0.7084
0.7082
0.7080
0.7078
0.7076
EVENT 1
EVENT 2
suture zone
Himalaya
foreland basins
broader region
dramatic slowdown in India's northward motion X
Yamdrok mélange
Liuqu conglomerate
sedimentary hiatus
intraformational conglomerates
deformation & Eohimalayan metamorphism
UHP metamorphism - Tso Morari eclogites (NW India) X
Sangdanlin X
Qumiba X
1st arrival of ophiolitic detritus
Sabathu Formation (NW India)
Ghazij Formation (Pakistan)
X youngest known subduction-related Gangdese granites
X youngest known subduction-related Linzizong volcanics
X youngest known marine sediments in Tethyan Himalaya (Qumiba)
rapid uplift and unroofing of Gangdese granites
Gangrinboche facies molasse
Indus molasse
Great Counter (Renbu-Zedong) thrust
E-W directed extension of Tibetan Plateau
North Himalayan granite-gneiss domes
South Tibet Detachment Fault
High Himalayan crystalline series
displacement on MCT
Siwalik Group molasse
Balakot Formation
?
Murree Formation
regional sediment flux
South China Sea spreading
sinistral offset on Red River Fault

Figure 7

Tethys must have been eliminated prior to eventual ocean closure. Remnants of features that developed as part of the Tethyan ocean floor are potentially preserved along the YTSZ, or their demise may be recorded in the sedimentary record. Investigations along the YTSZ over the past decade, together with a critical analysis of other published data (in both western and extensive Chinese literature) on the region, again provide pertinent information. A key is the recognition of the remnants of an intraoceanic subduction system(s) [*Aitchison and Davis*, 2004; *Aitchison et al.*, 2000] that are locally preserved along the suture in Tibet. This system must have collided either with India or Asia prior to the closure of Tethys.

[37] It has long been recognized that an intraoceanic island arc in NW India and Pakistan, the Kohistan/Dras arc [*Petterson and Treloar*, 2004; *Robertson and Degnan*, 1994; *Searle et al.*, 1999] collided along the Shyok suture zone (a lateral correlative of the Bangong-Nujiang suture zone [*Searle*, 1996; *Weinberg et al.*, 2000; *Ahmad et al.*, 2005]) with the southern margin of Eurasia during the Late Cretaceous [*Treloar et al.*, 1996, 1989]. Neotethyan oceanic lithosphere was already being subducted under the southern margin of the Kohistan arc prior to its accretion and this continued after it became part of Eurasia. We specifically note here that none of the intraoceanic island arc remnants we have reported [*Aitchison et al.*, 2000, 2004; *McDermid et al.*, 2002] from along the YTSZ are regarded as correlatives of the Kohistan arc. Instead, they represent fragments of an entirely separate intraoceanic system(s) and are correlatives of ophiolitic suites in the Ladakh region of NW India, including the Karzog, Nidar, and Spongtang ophiolites and the Spong arc [*Ahmad et al.*, 2005; *Corfield et al.*, 2001; *Mahéo et al.*, 2004]. All of these terranes were also thrust southward over the leading edge of India prior to continent-continent collision.

[38] A detailed examination of clastic sedimentary rocks across southern Tibet provides a record of events along the northern margin of India during the Paleogene (Figure 8). Our investigations in the region [*Aitchison et al.*, 2002a; *Davis et al.*, 2002, 2004] allow us to distinguish more than one series of molasse deposits, and provide improved age constraints for these units. Paleocene–early Eocene Liuqu conglomerates occur within the suture zone and contain SSZ-sourced ophiolitic detritus together with abundant red oceanic radiolarian chert clasts. Although these sediments crop out within the suture zone, they are notably devoid of Eurasia-sourced clasts. Instead, they record the oblique collision of an intraoceanic island arc with the northern margin of India [*Davis et al.*, 2002].

[39] In southern central Tibet, at Sangdanlin, a well-preserved sedimentary succession records a transition from Upper Cretaceous Indian margin-derived quartzarenites interbedded with shallow marine carbonates into Paleocene deep marine siliceous shales and radiolarites [*Ding*, 2003]. upper Paleocene conglomerates and sandstones appear abruptly near the top of the radiolarite succession. The presence of serpentinite clasts and other ophiolitic material [*Ding et al.*, 2005; J. C. Aitchison, personal observations, 2004] is consistent with derivation from intraoceanic island arc terranes such as those previously documented from the suture zone [*Aitchison et al.*, 2000; *Corfield et al.*, 2001; *McDermid et al.*, 2002]. Radiolarians assigned to the RP6 zone constrain the timing of the first appearance of ophiolitic detritus to the late Paleocene (~57 Ma). The detritus (Figure 6c) is the first indication that the northern edge of the Indian passive margin was beginning to collide with an intraoceanic island arc. In this context, we note a recent report in the Chinese literature [*G. B. Li et al.*, 2005] of coarse-grained Paleocene–early Eocene sedimentary rocks, the Jiachala Formation, in the northern Tethyan Himalaya NE of Gyantse. We suggest that the transition from shallow to deep marine sedimentation, at ~55 Ma, reflects tectonic loading of the northern margin of India during its approach and entry into the trench.

[40] Farther south of the suture zone, near Tingri, the same tectonic event is recorded with disruption of carbonate sedimentation within northern Himalayan Tethyan sediments [*Wan et al.*, 2002]. Detrital Cr-rich spinels, together with other grains consistent with intraoceanic arc derivation, first appear in lower Eocene (Ypresian) sediments [*Zhu et al.*, 2005] indicating southward propagation of material being shed off the arc-continent collision by 52 Ma. There is an apparent ~5 Ma lag between the first appearance of ophiolite-sourced material in northern Tethyan Himalayan sediments immediately adjacent to the YTSZ and those in outcrops rock shallow marine strata presently located 65 km to the south across regional strike at Qumiba. This is compatible with shortening estimates [*Johnson*, 2002] and the extent of northward motion of India (at 5 cm/yr) over that interval [*Acton*, 1999].

[41] Paleocene sediments south of the Himalaya in Pakistan, India and Nepal all contain detrital material including Cr-rich spinels consistent with a collision between and intraoceanic island arc and the northern margin of India. Spinel compositions, and accompanying trace element data [*Najman*, 2006; *Najman and Garzanti*, 2000] indicate derivation from SSZ ophiolitic rocks such as those present along the suture zone. Notably, although ophiolitic detritus ± red radiolarian chert ± basaltic/andesitic volcanic material is recorded, there are no reports of any clasts diagnostic of a collision between India and Asia. Cr-spinel is also reported as a detrital component of sandstones in the Jialazi Formation at Tso Jiangding [*Ding et al.*, 2005]. These sandstones are part of the fore-arc succession that developed along the southern margin of Eurasia. Compositions of the Cr-spinel grains suggest they originated in a SSZ environment. Unlike occurrences of detrital Cr-spinel south of the suture, there is no a priori reason why the presence of these detrital grains

Figure 7. Plot of significant geological phenomena recorded in rocks of southern Tibet and elsewhere in the region that are potentially related to collision of an island arc system with India at around ~55 Ma (event 1) followed India-Asia collision at around 35 Ma (event 2). Note the hiatus in collision-related events between these two time periods. O isotope curve (red dashed line) is after *Zachos et al.* [2001], and Sr isotope curve (green dashed line) follows the compilation of *McArthur and Howarth* [2004] for GTS 2004 [*Gradstein et al.*, 2004]. Figure produced with the assistance of TS-Creator (http://www.stratigraphy.org).

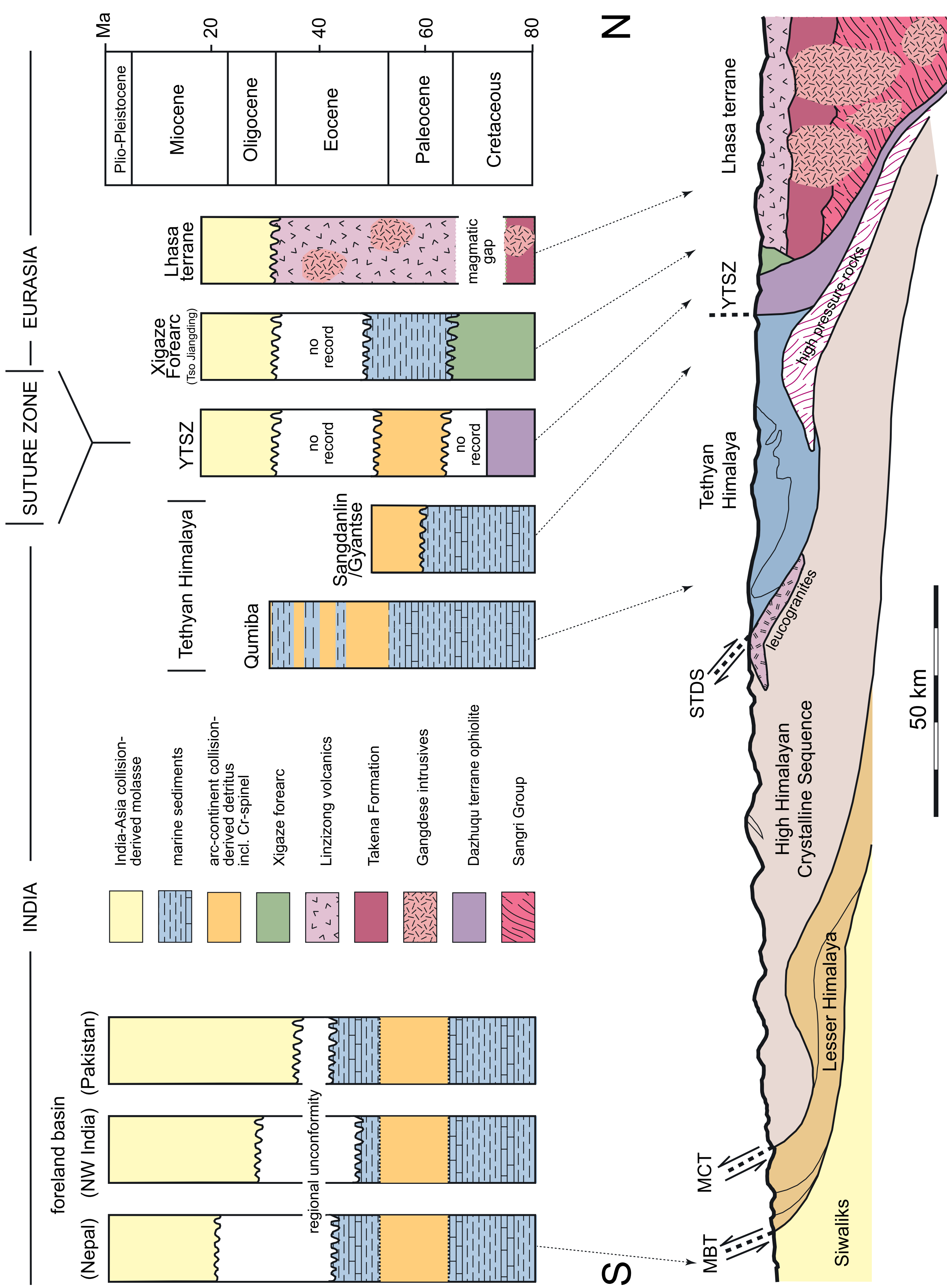
INDIA
SUTURE ZONE
EURASIA
foreland basin
(Nepal)
(NW India)
(Pakistan)
regional unconformity
Tethyan Himalaya
Qumiba
Sangdanlin /Gyantse
YTSZ
Xigaze Forearc (Tso Jiangding)
Lhasa terrane
no record
magmatic gap
Ma
20
40
60
80
Plio-Pleistocene
Miocene
Oligocene
Eocene
Paleocene
Cretaceous
India-Asia collision-derived molasse
marine sediments
arc-continent collision-derived detritus incl. Cr-spinel
Xigaze forearc
Linzizong volcanics
Takena Formation
Gangdese intrusives
Dazhuqu terrane ophiolite
Sangri Group
S
N
MBT
MCT
STDS
YTSZ
Siwaliks
Lesser Himalaya
High Himalayan Crystalline Sequence
leucogranites
Tethyan Himalaya
high pressure rocks
Lhasa terrane
50 km

Figure 8

should indicate that collision had occurred as these spinel grains accumulated in a SSZ (fore arc) setting and could have been locally sourced.

[42] When combined with reinterpretation of published data from the region, the sedimentary record provides abundant evidence for late Paleocene collision of an intraoceanic subduction system with the northern margin of India. Ophiolitic successions along the Indus-YTSZ were emplaced onto the northern margin of India [*Aitchison et al.*, 2000] during this episode. Analogous obduction events have also been reported from farther west in Pakistan [*Beck et al.*, 1995; *Sarwar*, 1992] and India [*Corfield et al.*, 2001; *Mahéo et al.*, 2004]. Similarity in the nature and timing of events over such an extensive strike length has major significance for regional tectonic modeling. Paleomagnetically constrained reconstructions indicate that the northern margin of Greater India was located at low northerly (3–12°N) latitudes at 55 Ma [*Ali and Aitchison*, 2005], in approximately the same location as that for the earlier formed intraoceanic island arc [*Abrajevitch et al.*, 2005]. Interestingly, the postulated position of this intraoceanic zone of plate convergence coincides with the southernmost of a series of zones of relatively high P wave velocity material within the mantle, which are interpreted to represent subducted Tethyan slabs [*Van der Voo et al.*, 1999].

[43] Collision and southward obduction of remnants of an intraoceanic island arc that included ophiolitic rocks onto northern India at 55 Ma also provides a possible explanation for the development of eclogites in the western Himalaya of NW India at Tso Morari [*De Sigoyer et al.*, 2000; *Searle*, 2001] as well as those in the Kaghan valley in Pakistan [*O'Brien et al.*, 2001; *Treloar et al.*, 2003]. Similar examples where the formation of eclogite and its subsequent rapid exhumation are manifestations of intraoceanic island arc collision with continental margins are well documented (e.g., New Caledonia [*Aitchison et al.*, 1995; *Cluzel et al.*, 2001] and Papua New Guinea where the youngest known eclogites (4.3 ± 0.4 Ma) are exposed on Earth's surface [*Baldwin et al.*, 2004]). We suggest that during the Paleocene steeply subducting oceanic lithosphere rapidly dragged attached continental crust on the northern edge of the Indian Plate into an intraoceanic subduction zone. This likely allowed continental crust to enter deep levels of the subduction zone for long enough to experience UHP metamorphism [*Leech et al.*, 2005] before isostatically rebounding to higher crustal levels. The formation and preservation of such rocks along, and near, the suture marking the boundary are consistent with India colliding with more than one subduction system as it traveled northward toward Asia. Furthermore, the P-T-t path experienced by these [*O'Brien et al.*, 2001] is entirely consistent with a such a model. Development of synkinematic muscovite during south directed thrusting and tight-to-isoclinal folding of the northernmost sections of Tibetan zone rocks [*Burg and Chen*, 1984; *Ratschbacher et al.*, 1994; *Wiesmayr and Grasemann*, 2002] was also associated with this orogenic event as was development of regionally extensive mud-matrix mélange. The presence of radiolarians as young as the Paleocene-Eocene boundary in the Yamdrok mélange [*Liu and Aitchison*, 2002], a unit which crops out south of the YTSZ, is consistent with its development during this event. A postcollision return to marine conditions is reflected in sedimentary rocks such as those unconformably overlying the Waziristan ophiolite in NW Pakistan [*Beck et al.*, 1995].

[44] If multiple plate boundaries once existed between India and Asia, this potentially provides a simple explanation for the marked slowdown (21.1 to 9.5 cm/yr) in the northward migration of India toward Asia at around 55 Ma [*Acton*, 1999; *Klootwijk et al.*, 1992a]. Notably, anything >11 cm/yr of convergence is beyond that observed across existing convergent plate margins, which have a median convergence rate of 7 cm/yr [*Gordon and Stein*, 1992]. If, however, more than one convergent plate boundary existed between India and Asia, then the net convergence rate between these two continental masses would have been the sum of the rates across individual plate boundaries that lay between them and could thus have totaled ~20 cm/yr. Once Indian continental crust entered the intraoceanic subduction system then the unsubductable nature of buoyant continental crust would have resulted in the failure of the associated convergent plate margin. The removal of this destructive plate boundary dramatically slowed down the net convergence rate between India and Asia to 9.5 cm/yr, a speed closer to that commonly observed across a single active subduction zone associated with orthogonal convergence.

5. Discussion

[45] In modern systems, involving entities of lesser magnitude than India and Asia, the effects of collision are geologically immediate. It is therefore curious that in the greatest collision system known on Earth, there is an apparent time lag of 25 Ma between the suggested timing of initial contact of buoyant continental lithospheric masses and the appearance of any of the orogenic effects associated with that collision. It is also anomalous that the continental collision is postulated to have begun at a time for which robust paleomagnetic data clearly indicate considerable separation between the supposedly colliding entities. We therefore contend that the imprecise nature of age determinations for key stratigraphic units, misinterpretation of

Figure 8. Schematic cross section from southern Tibet across the Himalaya [see *Dezes*, 1999] depicting the ages of key units that constrain the timing of the Paleocene–early Eocene collision of an intraoceanic island arc system with northern India followed by continent-continent collision between India and Asia in the Oligocene. (For location details in southern Tibet, refer to Figure 1b.) Paleocene–early Eocene sedimentary rocks include molasse (Liuqu conglomerate) along the suture zone or its distal equivalents that contain intraoceanic material derived from the suture zone. Formation of these units is related to the collision of an intraoceanic island arc with northern India and predates continental collision. The development of orogen-derived molasse (Gangrinboche conglomerates), which contains detritus from north of the suture, indicates that continental collision has taken place by the late Oligocene. YTSZ, Yarlung Tsangpo suture zone; STDS, South Tibet detachment system; MCT, Main Central thrust; MBT, Main Boundary thrust.

indirect geological signals, and inappropriate combination of proxies from multiple unrelated events have all contributed to the entrenchment of the 55 Ma India-Asia collision hypothesis. Improved age constraints and recently published new data permit the discrimination of multiple events affecting the northern margin of India during its northward migration. A distinct temporal gap exists between Paleocene–early Eocene and late Oligo-Miocene events previously attributed to the same collision event and there is no reliable evidence for any collisional continuum or so-called "soft collision." Recognition and separation of two temporally discrete unrelated events along the northern margin of India resolves the difficulty of explaining why responses to the collision between India and Asia lagged more than 25 Ma behind its inception.

[46] Reassessment of the India-Asia collision provides a means to reconcile disparate events and eliminates the requirement for special explanations such as soft collision or an enormous appendage to Greater India. Data now available are more appropriately reconciled with a multiple collision model in which the northbound Indian continental margin collided with an intraoceanic island arc system during the Paleocene. Events of this nature typically generate short-lived orogeny [*Dewey*, 2005], and we believe the subtle and, in many places, overprinted signature of this event has been misinterpreted. Remnants of this system were emplaced on northern India and were swept farther northward until India eventually collided with the southern margin of Eurasia during the Oligocene. The response to this second collision was immediate and involved cessation of calc-alkaline arc magmatism along the southern margin of Asia, uplift of the Tibetan Plateau, collisional orogenesis, molasse sedimentation, and readjustment of plate boundaries throughout eastern Asia. As the timing of collision initiation is a key boundary condition in models ranging from those involving the rates of orogenic processes to global climate change in response to plateau uplift, we suggest that such hypotheses now require critical reassessment.

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References

Abrajevitch, A., J. R. Ali, J. C. Aitchison, X. Badengzhu, A. M. Davis, J. B. Liu, and S. V. Ziabrev (2005), Neotethys and the India-Asia collision: Insights from a palaeomagnetic study of the Dazhuqu ophiolite southern Tibet, *Earth Planet. Sci. Lett.*, *233*, 87–102.

Achache, J., V. Courtillot, and Y. X. Zhou (1984), Paleogeographic and tectonic evolution of southern Tibet since Middle Cretaceous time; new paleomagnetic data and synthesis, *J. Geophys. Res.*, *89*, 10,311–310,339.

Acton, G. D. (1999), Apparent polar wander of India since the Cretaceous with implications for regional tectonics and true polar wander, in *The Indian Subcontinent and Gondwana: A Palaeomagnetic and Rock Magnetic Perspective*, edited by T. Radhakrishna et al., *Geol. Soc. India Mem.*, *44*, 129–175.

Ahmad, T., N. B. W. Harris, R. Islam, P. P. Khanna, H. K. Sachan, and B. K. Mukherji (2005), Contrasting mafic magmatism in the Shyok and Indus Suture Zones: Geochemical constraints, *Himalayan Geol.*, *26*, 33–40.

Aitchison, J. C., and A. M. Davis (2004), Evidence for the multiphase nature of the India-Asia collision from the Yarlung Tsangpo suture zone, Tibet, in *Aspects of the Tectonic Evolution of China*, edited by J. G. Malpas et al., *Geol. Soc. Spec. Publ.*, *226*, 217–233.

Aitchison, J. C., G. L. Clarke, S. Meffre, and D. Cluzel (1995), Eocene arc-continent collision in New Caledonia and implications for regional southwest Pacific tectonic evolution, *Geology*, *23*, 161–164.

Aitchison, J. C., et al. (2000), Remnants of a Cretaceous intra-oceanic subduction system within the Yarlung-Zangbo suture (southern Tibet), *Earth Planet. Sci. Lett.*, *183*, 231–244.

Aitchison, J. C., A. M. Davis, Badengzhu, and H. Luo (2002a), New constraints on the India-Asia collision: The lower Miocene Gangrinboche conglomerates, Yarlung Tsangpo suture zone, SE Tibet, *J. Asian Earth Sci.*, *21*, 253–265.

Aitchison, J. C., A. Abrajevitch, J. R. Ali, Badengzhu, A. M. Davis, H. Luo, J. B. Liu, I. R. C. McDermid, and S. Ziabrev (2002b), New insights into the evolution of the Yarlung Tsangpo suture zone, Xizang (Tibet), China, *Episodes*, *25*, 90–94.

Aitchison, J. C., A. M. Davis, J. R. Ali, Badengzhu, J. B. Liu, L. Hui, I. R. C. McDermid, and S. V. Ziabrev (2004), Stratigraphic and sedimentological constraints on the age and tectonic evolution of the Neotethyan ophiolites along the Yarlung Tsangpo suture zone, Tibet, in *Ophiolites in Earth History*, edited by Y. Dilek et al., *Geol. Soc. Spec. Publ.*, *218*, 147–164.

Ali, J. R., and J. C. Aitchison (2004), Problem of positioning Paleogene Eurasia: A review; efforts to resolve the issue; implications for the India-Asia collision, in *Continent-Ocean Interactions Within the East Asia Marginal Seas*. *Geophys. Monogr. Ser.*, vol. 149, edited by P. D. Clift et al., pp. 23–35, AGU, Washington, D. C.

Ali, J. R., and J. C. Aitchison (2005), Greater India, *Earth Science Reviews*, *72*, 169–188.

Ali, J. R., and J. C. Aitchison (2006), Positioning Palaeogene Eurasia problem: Solution for 60-50 Ma and broader tectonic implications, *Earth Planet. Sci. Lett.*, *251*, 148–155, doi:10.1016/j.epsl.2006.1009.1003.

Ali, J. R., D. J. Ward, C. King, and A. Abrajevitch (2003), First Palaeogene sedimentary rock palaeomagnetic pole from stable western Eurasia and tectonic implications, *Geophys. J. Int.*, *154*, 463–470.

Bajpai, S., R. C. Whatley, G. V. R. Prasad, and J. E. Whittaker (2004), An Oligocene non-marine ostracod fauna from the Basgo Formation (Ladakh Molasse), NW Himalaya, India, *J. Micropalaeontol.*, *23*, 3–9.

Baldwin, S. L., B. D. Monteleone, L. E. Webb, P. G. Fitzgerald, M. Grove, and E. June Hill (2004), Pliocene eclogite exhumation at plate tectonic rates in eastern Papua New Guinea, *Nature*, *431*, 263–267.

Bazhenov, M. L., and A. V. Mikolaichuk (2002), Paleomagnetism of Paleogene basalts from the Tien Shan, Kyrgyzstan: Rigid Eurasia and the dipole geomagnetic field, *Earth Planet. Sci. Lett.*, *195*, 155–166.

Beaumont, C., R. A. Jamieson, M. H. Nguyen, and B. Lee (2001), Himalayan tectonics explained by extrusion of a low-viscosity crustal channel coupled to focused surface denudation, *Nature*, *414*, 738–742.

Beaumont, C., R. A. Jamieson, M. H. Nguyen, and S. Medvedev (2004), Crustal channel flows: 1. Numerical models with applications to the tectonics of the Himalayan-Tibetan orogen, *J. Geophys. Res.*, *109*, B06406, doi:10.1029/2003JB002809.

Beck, R. A., et al. (1995), Stratigraphic evidence for an early collision between northwest India and Asia, *Nature*, *373*, 55–58.

Besse, J., and V. Courtillot (1991), Revised and synthetic apparent polar wander paths of the African, Eurasian, North American and India plates, and true polar wander since 200 Ma, *J. Geophys. Res.*, *96*, 4029–4050.

Besse, J., and V. Courtillot (2002), Apparent and true polar wander and the geometry of the geomagnetic field over the last 200 Myr, *J. Geophys. Res.*, *107*(B11), 2300, doi:10.1029/2000JB000050. (Correction to "Apparent and true polar wander and the geometry of the geomagnetic field over the last 200 Myr", *J. Geophys. Res.*, *108*(B10), 2469, doi:10.1029/2003JB002684 (2003).

Blow, R. A., and N. Hamilton (1975), Paleomagnetic evidence from DSDP cores of northward drift of India, *Nature*, *257*, 570–572.

Bossart, P., and R. Ottiger (1989), Rocks of the Murree Formation in northern Pakistan: Indicators of a descending foreland basin of late Palaeocene to middle Eocene age, *Eclogae Geol. Helv.*, *82*, 133–165.

Brown, B., R. D. Müller, H. I. M. Struckmeyer, C. Gaina, H. Stagg, and P. Symonds (2003), Formation and evolution of Australian passive margins: Implications for locating the boundary between continental

and oceanic crust, in *Evolution and Dynamics of the Australian Plate*, edited by R. R. Hillis et al., *Spec. Pap. Geol. Soc. Am.*, *372*, 223–243.
Burbank, D. W., R. A. Beck, and T. J. Mulder (1996), The Himalayan Foreland Basin, in *The Tectonic Evolution of Asia,* edited by A. Yin et al., pp. 149–188, Cambridge Univ. Press, New York.
Burg, J. P. (1992), Himalayan orogen and global tectonics seen from the Tsangpo suture zone of Tibet (China), in *Himalayan Orogen and Global Tectonics,* edited by A. K. Sinha, pp. 35–44, A. A. Balkema, Brookfield, Vt.
Burg, J. P., and G. M. Chen (1984), Tectonics and structural zonation of southern Tibet, China, *Nature*, *311*, 219–223.
Burg, J. P., A. Leyreloup, J. Girardeau, and G. M. Chen (1987), Structure and metamorphism of a tectonically thickened continental crust; the Yalu Tsangpo suture zone (Tibet), *Philos. Trans. R. Soc. London, Ser. A*, *321*, 67–86.
Chung, S.-L., et al. (2005), Tibetan tectonic evolution inferred from spatial and temporal variations in post-collisional magmatism, *Earth Sci. Rev.*, *68*, 173–196.
Clift, P. D., A. Carter, M. Krol, and E. Kirby (2002), Constraints of India-Eurasia collision in the Arabian Sea region taken from the Indus Group, Ladakh Himalaya, India, in *The Tectonic and Climatic Evolution of the Arabian Sea Region,* edited by P. D. Clift et al., *Geol. Soc. Spec. Publ.*, *195*, 97–116.
Cluzel, D., J. C. Aitchison, and C. Picard (2001), Tectonic accretion and underplating of mafic terranes in the Late Eocene intraoceanic fore-arc of New Caledonia (southwest Pacific): Geodynamic implications, *Tectonophysics*, *340*, 23–59.
Corfield, R. I., M. P. Searle, and R. B. Pedersen (2001), Tectonic setting, origin, and obduction history of the Spontang Ophiolite, Ladakh Himalaya, NW India, *J. Geol.*, *109*, 715–736.
Coulon, C., H. Maluski, C. Bollinger, and S. Wang (1986), Mesozoic and Cenozoic volcanic rocks from central and southern Tibet: ^{39}Ar–^{40}Ar dating, petrological characteristics and geodynamic significance, *Earth Planet. Sci. Lett.*, *79*, 281–302.
Critelli, S., and E. Garzanti (1994), Provenance of the lower Tertiary Murree redbeds (Hazara-Kashmir Syntaxis, Pakistan) and initial rising of the Himalayas, *Sediment. Geol.*, *89*, 265–284.
Davis, A. M., J. C. Aitchison, Badengzhu, H. Luo, and S. Zyabrev (2002), Paleogene island arc collision-related conglomerates, Yarlung-Tsangpo suture zone, Tibet, *Sediment. Geol.*, *150*, 247–273.
Davis, A. M., J. C. Aitchison, Badengzhu, and L. Hui (2004), Conglomerates of the Yarlung Tsangpo suture zone, southern Tibet, in *Aspects of the Tectonic Evolution of China*, edited by J. G. Malpas et al., *Geol. Soc. Spec. Publ.*, *226*, 235–246.
Debon, F., P. Le Fort, S. M. F. Sheppard, and J. Sonet (1986), The four plutonic belts of the Transhimalaya-Himalaya; a chemical, mineralogical, isotopic, and chronological synthesis along a Tibet-Nepal section, *J. Petrol.*, *27*, 219–250.
DeCelles, P. G., G. E. Gehrels, J. Quade, and T. P. Ohja (1998a), Eocene-early Miocene foreland basin development and the history of Himalayan thrusting, western and central Nepal, *Tectonics*, *17*, 741–765.
DeCelles, P. G., G. E. Gehrels, J. Quade, T. P. Ojha, P. A. Kapp, and B. N. Upreti (1998b), Neogene foreland basin deposits, erosional unroofing, and the kinematic history of the Himalayan fold-thrust belt, western Nepal, *Geol. Soc. Am. Bull.*, *110*, 2–21.
De Sigoyer, J., V. Chavagnac, J. Blichert-Toft, I. M. Villa, B. Luais, S. Guillot, M. Cosca, and G. Mascle (2000), Dating the Indian continental subduction and collisional thickening in the northwest Himalaya: Multichronology of the Tso Marari eclogites, *Geology*, *28*, 487–490.
Dewey, J. F. (2005), Orogeny can be very short, *Proc. Natl. Acad. Sci. U. S. A.*, *102*, 15,286–15,293.
Dezes, P. (1999), Tectonic and metamorphic evolution of the central Himalayan domain in southeast Zanskar (Kashmir, India), *Mem. Geol. Lausanne*, *32*, 1–160.
Ding, L. (2003), Paleocene deep-water sediments and radiolarian faunas: Implications for evolution of Yarlung-Zangbo foreland basin, southern Tibet, *Sci. China, Ser. D*, *46*, 84–91.
Ding, L., P. Kapp, and X. Wan (2005), Paleocene–Eocene record of ophiolite obduction and initial India-Asia collision, south central Tibet, *Tectonics*, *24*, TC3001, doi:10.1029/2004TC001729.
Dong, X. B., Z. M. Wang, C. Z. Tan, H. X. Yang, L. R. Cheng, and Y. X. Zhou (1991), New results of paleomagnetic studies of the Qinghai-Tibetan plateau, *Geol. Rev.*, *37*, 160–164.
Edwards, R. A., R. B. Whitmarsh, and R. Scrutton (1997), A synthesis of the crustal structure of the transform continental margin off Ghana, northern Gulf of Guinea, *Geo Mar. Lett.*, *17*, 12–20.
Einsele, G., et al. (1994), The Xigaze forearc basin: Evolution and facies architecture (Cretaceous, Tibet), *Sediment. Geol.*, *90*, 1–32.
Ernst, W. G. (1999), Hornblende, the continent maker: Evolution of H_2O during circum-Pacific subduction versus continental collision, *Geology*, *27*, 675–678.
Fang, A. M., Z. S. An, X. H. Liu, Y. S. Pan, J. L. Li, L. J. Yu, F. X. Huang, and J. R. Tao (2006), The age of the plant fossil assemblage in the Liuqu Conglomerate of southern Tibet and its tectonic significance, *Progr. Nat. Sci.*, *16*, 55–64.
Garzanti, E., and T. Van Haver (1988), The Indus clastics: Forearc basin sedimentation in the Ladakh Himalaya (India), *Sediment. Geol.*, *59*, 237–249.
Girardeau, J., J. Marcoux, and Y. Zao (1984), Lithologic and tectonic environment of the Xigaze ophiolite (Yarlung Zangbo suture zone, southern Tibet, China), and kinematics of its emplacement, *Eclogae Geol. Helv.*, *77*, 153–170.
Gordon, R. G., and S. Stein (1992), Global tectonics and space geodesy, *Science*, *256*, 333–342.
Gradstein, F. M., et al. (2004), *A Geologic Time Scale*, 589 pp., Cambridge Univ. Press, New York.
Hall, R. (2002), Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: Computer-based reconstructions, model and animations, *J. Asian Earth Sci.*, *20*, 353–431.
Harrison, T. M., P. Copeland, W. S. F. Kidd, and A. Yin (1992), Raising Tibet, *Science*, *255*, 1663–1670.
Hill, K. C., and A. Raza (1999), Arc-continent collision in Papua New Guinea: Constraints from fission track thermochronology, *Tectonics*, *18*, 950–966.
Hodges, K. V. (2000), Tectonics of the Himalaya and southern Tibet from two perspectives, *Geol. Soc. Am. Bull.*, *112*, 324–350.
Huang, B. C., J. D. A. Piper, Y. C. Wang, H. Y. He, and R. X. Zhu (2005), Paleomagnetic and geochronological constraints on the post-collisional northward convergence of the southwest Tian Shan, NW China, *Tectonophysics*, *409*, 107–124.
Huang, C. Y., P. B. Yuan, C. W. Lin, T. K. Wang, and C. P. Chang (2000), Geodynamic processes of Taiwan arc-continent collision and comparison with analogs in Timor, Papua New Guinea, Urals and Corsica, *Tectonophysics*, *325*, 1–21.
Intergovernmental Oceanographic Commission, International Hydrographic Organization, and British Oceanographic Data Centre (2003), Centenary edition of the GEBCO Digital Atlas published on CD-ROM on behalf of the Intergovernmental Oceanographic Commission and the International Hydrographic Organization as part of the General Bathymetric Chart of the Oceans, Liverpool, U. K.
Jaeger, J.-J., V. Courtillot, and P. Tapponnier (1989), Paleontological view of the ages of the Deccan Traps, the Cretaceous/Tertiary boundary, and the India-Asia collision, *Geology*, *17*, 316–319.
Jain, K. P., and R. Garg (1986), Revision and reassessment of a dinoflagellate cyst assemblage from Sangchamalla Formation (Upper Flysch), Malla Johar area, Kumaon Himalaya, India, *Palaeobotanist*, *35*, 61–68.
Jamieson, R. A., C. Beaumont, S. Medvedev, and M. H. Nguyen (2004), Crustal channel flows: 2. Numerical models with implications for metamorphism in the Himalayan-Tibetan orogen, *J. Geophys. Res.*, *109*, B06407, doi:10.1029/2003JB002811.
Johnson, M. (2002), Shortening budgets and the role of continental subduction during the India-Asia collision, *Earth Sci. Rev.*, *59*, 101–123.
Juyal, K. P., S. K. Parcha, N. S. Mathur, and J. Singh (2002), Microfauna and age of the Sangcha Malla Formation of Garhwal Tethys Himalaya, India, *Current Sci.*, *82*, 458–462.
Klootwijk, C. T., J. S. Gee, J. W. Peirce, and G. M. Smith (1991), Constraints on the India-Asia convergence: Paleomagnetic results from Ninetyeast Ridge, *Proc. Ocean Drill. Program Sci. Results*, *121*, 777–882.
Klootwijk, C. T., J. S. Gee, J. W. Peirce, G. M. Smith, and P. L. McFadden (1992a), An early India-Asia contact; paleomagnetic constraints from Ninetyeast Ridge, ODP Leg 121; with Suppl. Data 92-15, *Geology*, *20*, 395–398.
Klootwijk, C. T., J. S. Gee, J. W. Peirce, G. M. Smith, and P. L. McFadden (1992b), An early India-Asia contact; paleomagnetic constraints from Ninetyeast Ridge, ODP Leg 121; with Suppl. Data 92-15, *Geology (Boulder)*, *20*, 395–398.
Leech, M. L., S. Singh, A. K. Jain, S. L. Klemperer, and R. M. Manickavasagam (2005), The onset of India-Asia continental collision: Early, steep subduction required by the timing of UHP metamorphism in the western Himalaya, *Earth Planet. Sci. Lett.*, *234*, 83–97.
Leloup, P. H., R. Lacassin, P. Tapponnier, U. Schärer, D. L. Zhong, X. H. Liu, L. S. Zhang, S. C. Ji, and P. T. Trinh (1995), The Ailao Shan–Red River shear zone (Yunnan, China), Tertiary transform boundary of Indochina, *Tectonophysics*, *251*, 3–84.
Leloup, P. H., N. Arnaud, R. Lacassin, J. R. Kienast, T. M. Harrison, T. T. T. Pan, A. Replumaz, and P. Tapponnier (2001), New constraints on the structure, thermochronology, and timing of the Ailao Shan-Red River shear zone, SE Asia, *J. Geophys. Res.*, *106*, 6683–6732.
Li, G. B., and X. Q. Wan (2003), Eocene microfossils in southern Tibet and the final closing of the Tibet-Tethys, *J. Stratigr.*, *27*, 99–108.

Li, G. B., X. Q. Wan, X. Qiherige, D. Y. Liang, and W. C. Liu (2002), Eocene fossil carbonate microfacies and sedimentary environment in Gamba-Tingri, southern Tibet, *Geol. China*, *29*, 401–406.

Li, G. B., X. Q. Wan, W. C. Liu, D. Y. Liang, and H. S. Yun (2005), Discovery of Paleogene marine stratum along the southern side of Yarlung-Zangbo suture zone and its implications in tectonics, *Sci. China, Ser. D*, *48*, 647–661.

Li, Q., Z. Jian, and X. Su (2005), Late Oligocene rapid transformations in the South China Sea, *Mar. Micropaleontol.*, *54*, 5–25.

Li, X. H., C. S. Wang, X. M. Hu, X. Q. Wan, Y. L. Xu, and W. J. Zhao (2000), The Pengqu Formation: A new Eocene stratigraphical unit in Tingri area, Tibet, *J. Stratigr.*, *24*, 244–248.

Liu, C. J., J. X. Yin, X. X. Sun, and Y. Y. Sun (1988), Marine Late Cretaceous–Early Tertiary sequences: The non-flysch deposits of the Xigaze forearc basin in south Xizang, *J. Inst. Geol. Chin. Acad. Sci.*, *3*, 130–157.

Liu, J. B., and J. C. Aitchison (2002), Upper Paleocene radiolarians from the Yamdrok mélange, south Xizang (Tibet), China, *Micropaleontology*, *48*, 145–154.

Lundberg, N., and R. J. Dorsey (1990), Rapid Quaternary emergence, uplift, and denudation of the Coastal Range, eastern Taiwan, *Geology*, *18*, 638–641.

Mahéo, G., H. Bertrand, S. Guillot, I. M. Villa, F. Keller, and P. Capiez (2004), The South Ladakh ophiolites (NW Himalaya, India): An intra-oceanic tholeiitic arc origin with implication for the closure of the Neo-Tethys, *Chem. Geol.*, *203*, 273–303.

Maluski, H., F. Proust, and X. C. Xiao (1982), $^{39}Ar/^{40}Ar$ dating of the trans-Himalayan calc-alkaline magmatism of southern Tibet, *Nature*, *298*, 152–154.

Marcoux, J., et al. (1982), Preliminary report of depositional sediments on top of volcanic member; Xigaze Ophiolite (Yarlung Zangbo suture zone); south Xingang (Tibet), *Ofioliti*, *2/3*, 395–396.

Mascle, J., P. Lohmann, and P. Clift (1997), Development of a passive transform margin: Côte d'Ivoire-Ghana transform margin: ODP Leg 159 preliminary results, *Geo Mar. Lett.*, *17*, 4–11.

McArthur, J. M., and R. J. Howarth (2004), Sr-isotope stratigraphy, in *A Geological Timescale 2004*, edited by F. Gradstein et al., pp. 96–104, Cambridge Univ. Press, New York.

McDermid, I. R. C., J. C. Aitchison, A. M. Davis, T. M. Harrison, and M. Grove (2002), The Zedong terrane: A Late Jurassic intra-oceanic magmatic arc within the Yarlung-Zangbo suture zone, southeastern Tibet, *Chem. Geol.*, *187*, 267–277.

Mehrotra, N. C., and A. K. Sinha (1978), Discovery of microplanktons and the evidences of younger age of the Sangcha Malla Formation (Upper Flysch) of Malla Johar area in the Tethyan Zone of Kumaun Himalaya, *Himalayan Geol.*, *8*, 1001–1004.

Mehrotra, N. C., and A. K. Sinha (1981), Further studies on microplankton from the Sangchamalla Formation (upper flysch) of Malla Johar area in the Tethyan zone of higher Kumaun Himalaya, in *Contemporary Geoscientific Researches in Himalaya: A Commemorative Volume in Honour of S. P., Nautiyal,* vol. 1, pp. 151–160, B. Singh, Dehra Dun, India.

Menzies, M. A. (Ed.) (1990), *Continental Mantle*, 184 pp., Clarendon, Oxford, U. K.

Métivier, F., Y. Gaudemer, P. Tapponnier, and M. Klein (1999), Mass accumulation rates in Asia during the Cenozoic, *Geophys. J.*, *137*, 280–318.

Miller, C., R. Schuster, U. Klötzli, W. Frank, and B. Grasemann (2000), Late Cretaceous-Tertiary magmatic and tectonic events in the Transhimalaya batholith (Kailas area, SW Tibet), *Schweiz. Mineral. Petrogr. Mitt.*, *80*, 1–20.

Miller, C., M. Thöni, W. Frank, R. Schuster, F. Melcher, T. Meisel, and A. Zanetti (2003), Geochemistry and tectonomagmatic affinity of the Yungbwa ophiolite, SW Tibet, *Lithos*, *66*, 155–172.

Molnar, P., and P. Tapponnier (1975), Cenozoic tectonics of Asia: Effects of a continental collision, *Science*, *189*, 419–426.

Molnar, P., P. England, and J. Martinod (1993), Mantle dynamics, uplift of the Tibetan Plateau, and the Indian monsoon, *Rev. Geophys.*, *31*, 357–396.

Najman, Y. (2006), The detrital record of orogenesis: A review of approaches and techniques used in the Himalayan sedimentary basins, *Earth Sci. Rev.*, *74*, 1–72.

Najman, Y., and E. Garzanti (2000), Reconstructing early Himalayan tectonic evolution and paleogeography from Tertiary foreland basin sedimentary rocks, northern India, *Geol. Soc. Am. Bull.*, *112*, 435–449.

Najman, Y., M. Pringle, L. Godin, and G. Oliver (2001), Dating of the oldest continental sediments from the Himalayan foreland basin, *Nature*, *410*, 194–197.

Najman, Y., M. Pringle, L. Godin, and G. Oliver (2002), A reinterpretation of the Balakot Formation: Implications for the tectonics of the NW Himalaya, Pakistan, *Tectonics*, *21*(5), 1045, doi:10.1029/2001TC001337.

Najman, Y., K. Johnson, N. White, and G. Oliver (2004), Evolution of the Himalayan foreland basin, *NW India, Basin Res.*, *16*, 1–24.

Nicolas, A., J. Girardeau, J. Marcoux, B. Dupre, X. Wan, Y. Cao, H. Zheng, and X. Xiao (1981), The Xigaze ophiolite (Tibet): A peculiar oceanic lithosphere, *Nature*, *294*, 414–417.

Niitsuma, N. (1999), Rupture and delamination of arc crust due to the arc-arc collision in the South Fossa magna, central Japan, *Isl. Arc*, *8*, 441–458.

O'Brien, P. J., N. Zotov, R. Law, M. A. Khan, and M. Q. Jan (2001), Coesite in Himalayan eclogite and implications for models of India-Asia collision, *Geology*, *29*, 435–438.

Otofuji, Y., S. Funahara, J. Matsuo, F. Murata, T. Nishiyama, X. Zheng, and K. Yaskawa (1989), Paleomagnetic study of western Tibet; deformation of a narrow zone along the Indus Zangbo suture between India and Asia, *Earth Planet. Sci. Lett.*, *92*, 307–316.

Otofuji, Y., K. Jun, F. Shoubu, F. Murata, and X. L. Zheng (1991), Paleomagnetic study of the Eocene Quxu pluton of the Gangdese belt: Crustal deformation along the Indus-Zangbo suture zone in southern Tibet, *Earth Planet. Sci. Lett.*, *107*, 369–379.

Patriat, P., and J. Achache (1984), India-Eurasia collision chronology has implications for crustal shortening and driving mechanism of plates, *Nature*, *311*, 615–621.

Petterson, M. G., and P. J. Treloar (2004), Volcanostratigraphy of arc volcanic sequences in the Kohistan arc, North Pakistan: Volcanism within island arc, back-arc-basin, and intra-continental tectonic settings, *J. Volcanol. Geotherm. Res.*, *130*, 147–178.

Rage, J. C., H. Cappetta, J. L. Hartenberger, J. J. Jaeger, J. Sudre, M. Vianey-Liaud, K., Kumar, G. V. R. Prasad, and A. Sahni (1995), Collision age, *Nature.*, *375*, 286.

Ratschbacher, L., W. Frisch, and G. Liu (1994), Distributed deformation in southern and western Tibet during and after the India-Asia collision, *J. Geophys. Res.*, *99*, 19,917–19,945.

Raymo, M. E., and W. F. Ruddiman (1992), Tectonic forcing of late Cenozoic climate, *Nature*, *359*, 117–122.

Richardson, A. N., and D. J. Blundell (1996), Continental collision in the Banda Arc, in *Tectonic Evolution of Southeast Asia,* edited by R. Hall et al., *Geol. Soc. Spec. Publ.*, *106*, 47–60.

Riisager, P., J. Riisager, N. Abrahamsen, and R. Waagstein (2002), New paleomagnetic pole and magnetostratigraphy of Faeroe Islands flood volcanics, North Atlantic igneous province, *Earth Planet. Sci. Lett.*, *201*, 261–276.

Robertson, A. H. F., and P. Degnan (1994), The Dras arc complex; lithofacies and reconstruction of a Late Cretaceous oceanic volcanic arc in the Indus suture zone, Ladakh Himalaya, *Sediment. Geol.*, *92*, 117–145.

Rowley, D. B. (1996), Age of initiation of collision between India and Asia: A review of stratigraphic data, *Earth Planet. Sci. Lett.*, *145*, 1–13.

Rowley, D. B. (1998), Minimum age of initiation of collision between India and Asia north of Everest based on the subsidence history of the Zhepure Mountain section, *J. Geol.*, *106*, 1–13.

Rowley, D. B., and B. S. Currie (2006), Palaeo-altimetry of the late Eocene to Miocene Lunpola basin, central Tibet, *Nature*, *439*, 677–681.

Ruddiman, W. F., and J. E. Kutzbach (1989), Forcing of Late Cenozoic northern hemisphere climate by plateau uplift in southern Asia and the American west, *J. Geophys. Res.*, *94*, 18,409–18,427.

Sarwar, G. (1992), Tectonic setting of the Bela Ophiolites, southern Pakistan, *Tectonophysics*, *207*, 359–381.

Schärer, U., H. X. Rong, and C. J. Allègre (1984), U-Pb geochronology of Gangdese (Transhimalaya) plutonism in the Lhasa-Xigaze region, Tibet, *Earth Planet. Sci. Lett.*, *69*, 311–320.

Schettino, A., and C. R. Scotese (2005), Apparent polar wander paths for the major continents (200 Ma to the present day): A palaeomagnetic reference frame for global plate tectonic reconstructions, *Geophys. J. Int.*, *163*, 727–759.

Searle, M. P. (1996), Geological evidence against large-scale pre Holocene offsets along the Karakoram Fault: Implications for the limited extrusion of the Tibetan Plateau, *Tectonics*, *15*, 171–186.

Searle, M. P. (2001), Dating the Indian continental subduction and collisional thickening in the northwest Himalaya: Multichronology of the Tso Morari eclogites: Comment, *Geology*, *29*, 191–192.

Searle, M. P., et al. (1987), The closing of Tethys and the tectonics of the Himalaya, *Geol. Soc. Am. Bull.*, *98*, 678–701.

Searle, M. P., D. W. J. Cooper, and A. J. Rex (1988), Collision tectonics of the Ladakh-Zanskar Himalaya, *Philos. Trans. R. Soc. London, Ser. A*, *326*, 117–150.

Searle, M. P., K. T. Pickering, and D. J. W. Cooper (1990), Restoration and evolution of the intermontane Indus molasse basin, Ladakh Himalaya, India, *Tectonophysics*, *174*, 301–314.

Searle, M. P., M. A. Khan, J. E. Fraser, S. J. Gough, and M. Q. Jan (1999), The tectonic evolution of the Kohistan-Karakoram collision belt along the Karakoram Highway transect, north Pakistan, *Tectonics*, *18*, 929–949.

Sinha, A. K. (Ed.) (1989), *Geology of the Higher Central Himalaya*, 219 pp., John Wiley, Hoboken, N. J.

Sun, X., and P. Wang (2005), How old is the Asian monsoon system?—Palaeobotanical records from China, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *222*, 181.

Symonds, P. A., S. Planke, O. Frey, and J. Skogseid (1998), Volcanic evolution of the western Australian continental margin and its implications for basin development, in *The Sedimentary Basins of Western Australia: Proceedings of the PESA Symposium,* vol. 2, edited by R. R. Purcell et al., pp. 33–54, Petrol. Explor. Soc. of Aust., Perth.

Tapponnier, P., G. Peltzer, A. Y. Le Dain, R. Armijo, and P. Cobbold (1982), Propagating extrusion tectonics in Asia: New insights from simple experiments with plasticine, *Geology*, *10*, 611–616.

Tatsumi, Y., and S. Eggins (Eds.) (1995), *Subduction Zone Magmatism*, 200 pp., Blackwell, Cambridge.

Torsvik, T. H., and M. A. Smethurst (1999), Plate tectonic modelling: Virtual reality with GMAP, *Comput. Geosci.*, *25*, 395–402.

Torsvik, T. H., R. Van der Voo, J. G. Meert, J. Mosar, and H. J. Walderhaug (2001), Reconstructions of the continents at about the 60th parallel, *Earth Planet. Sci. Lett.*, *187*, 55–69.

Treloar, P. J., P. G. Guise, M. P. Coward, M. P. Searle, B. F. Windley, M. G. Petterson, M. Q. Jan, and I. W. Luff (1989), K-Ar and Ar-Ar geochronology of the Himalayan collision in NW Pakistan; constraints on the timing of suturing, deformation, metamorphism and uplift, *Tectonics*, *8*, 881–909.

Treloar, P. J., M. G. Petterson, M. Qasin Jan, and M. A. Sullivan (1996), A re-evaluation of the stratigraphy and evolution of the Kohistan arc sequence, Pakistan Himalaya: Implications for magmatic and tectonic arc building processes, *J. Geol. Soc.*, *153*, 681–693.

Treloar, P. J., P. J. O'Brien, R. R. Parrish, and M. A. Khan (2003), Exhumation of early Tertiary, coesite-bearing eclogites from the Pakistan Himalaya, *J. Geol. Soc.*, *160*, 367–376.

Van der Voo, R. (1990), The reliability of paleomagnetic data, *Tectonophysics*, *184*, 1–9.

Van der Voo, R., W. Spakman, and H. Bijwaard (1999), Tethyan subducted slabs under India, *Earth Planet. Sci. Lett.*, *171*, 7–20.

Wan, X. Q., L. F. Jansa, and M. Sarti (2002), Cretaceous and Paleogene boundary strata in southern Tibet and their implication for the India-Eurasia collision, *Lethaia*, *35*, 131–146.

Wang, C. S., X. H. Li, X. M. Hu, and L. F. Jansa (2002), Latest marine horizon north of Qomolangma (Mt Everest): Implications for closure of Tethys seaway and collision tectonics, *Terra Nova*, *14*, 114–120.

Weinberg, R. F., W. J. Dunlap, and M. Whitehouse (2000), New field, structural and geochronological data from the Shyok and Nubra valleys, northern Ladakh: Linking Kohistan to Tibet, in *Tectonics of the Nanga Parbat Syntaxis and the Western Himalaya.* edited by A. Khan et al., *Geol. Soc. Spec. Publ.*, *170*, 253–276.

Westphal, M., J. P. Pozzi, X. Y. Zhou, L. S. Xing, and X. Y. Chen (1983), Palaeomagnetic data about southern Tibet (Xizang) - 1. The Cretaceous formations of the Lhasa block, *Geophys. J. R. Astron. Soc.*, *73*, 507–521.

Whitmarsh, R. B., G. Manatschal, and T. A. Minshull (2001), Evolution of magma-poor continental margins from rifting to seafloor spreading, *Nature*, *413*, 150–154.

Wiesmayr, G., and B. Grasemann (2002), Eohimalayan fold and thrust belt: Implications for the geodynamic evolution of the NW-Himalaya (India), *Tectonics*, *21*(6), 1058, doi:10.1029/2002TC001363.

Xu, R. H., U. Schaerer, and C. J. Allegre (1985), Magmatism and metamorphism in the Lhasa Block (Tibet): A geochronological study, *J. Geol.*, *93*, 41–57.

Xu, Y. L. (2000), Early Tertiary calcareous nannofossils from southern Tibet and the closing time of east Tethys in Tibet, *Geosci. J. Grad. Sch. China Univ. Geosci.*, *14*, 255–264.

Yin, A. (2006), Cenozoic tectonic evolution of the Himalayan orogen as constrained by along-strike variation of structural geometry, exhumation history, and foreland sedimentation, *Earth Sci. Rev.*, *76*, 1–131.

Yin, A., and T. M. Harrison (2000), Geologic evolution of the Himalayan-Tibetan Orogen, *Annu. Rev. Earth Planet. Sci.*, *28*, 211–280.

Zachos, J., M. Pagani, L. Sloan, E. Thomas, and K. Billups (2001), Trends, rhythms, and aberrations in global climate 65 Ma to Present, *Science*, *292*, 686–693.

Zhou, Y. X., L. Z. Lu, X. Y. Chen, and X. C. Yuan (1990), The paleomagnetic study of the Tibetan plateau and preliminary discussion on its tectonic evolution, in *Tectonic Evolution of the Himalayan Lithosphere: Paleomagnetism and Magnetotelluric Sounding of the Tibetan Plateau,* edited by X. C. Yuan et al., pp. 20–119, Geol. Publ. House, Beijing.

Zhu, B., W. S. F. Kidd, D. B. Rowley, B. S. Currie, and N. Shafique (2005), Age of initiation of the India-Asia collision in the east-central Himalaya, *J. Geol.*, *113*, 265–285.

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