Reply to comment by Eduardo Garzanti on "When and where did India and Asia collide?"

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[1] We thank Eduardo Garzanti for his comment [*Garzanti*, 2008] on our recent paper [*Aitchison et al.*, 2007]. A traditional approach is to apply Occam's razor and view our planet's most significant orogenic zone as a response to closure of a one-ocean, two-continent convergence system. However, a vast body of new data has been obtained in the decades following widespread acceptance of this conservative model by the scientific community. We contend that significant details are lost with this conventional view. Critically, it is now clear that the northern margin of India experienced not one but two quite discrete collisions during the Paleogene.

[2] The importance of definitions notwithstanding, semantic discussions regarding the definition of continent-continent collision and what is meant by the India-Asia event obfuscate the important issue of how this massive orogen really developed. In particular, the possibility of "preconditioning" the northern margin of India prior to its impact with Asia is easily overlooked. If, as we suggest, India experienced other collisions prior to that with Asia, then this would have affected the nature of its leading edge prior to the terminal episode. We certainly do not dispute the existence of geological phenomena that record a 55 Ma event in the Himalaya-Tibet orogen and elsewhere regionally; we dispute only their interpretation. All aspects of the 55 Ma data set are consistent with a collision between an intraoceanic island arc and the northern edge of Greater India.

[3] We contend that any Himalaya-Tibet orogen evolution model has to have an India-Asia contact (t_0) that is compatible with what is known from both a plate tectonic perspective and the geology of the suture zone. There is no a priori reason why the 55 Ma event was a collision between India and Asia. Indeed, a critical test of the existing 55 Ma hypothesis is whether or not the relative positions of India and Asia at that time could have allowed collision between these continents. Plate tectonic studies can be used (1) to constrain India's motion history, (2) to constrain India's precollision size, (3) to constrain the position of "stable" Asia, and (4) to constrain the position of Asia's southern edge; geological investigations from the Indus-Yarlung Tsangpo suture zone allow us (5) to examine the elements involved in the convergence system and (6) to obtain direct information concerning the timing of collision.

[4] In summary, the first point has been tightly fixed for at least a decade [e.g., *Acton*, 1999; *Besse and Courtillot*, 2002]; the second point was recently evaluated by *Ali and Aitchison* [2005]; the third point has been addressed by *Ali and Aitchison* [2004, 2006]; our knowledge of the fourth point is limited, but with the third point now much better known we can be confident of where the edge of southern Asia likely lay during the early Cenozoic and mid-Cenozoic (and perhaps more importantly where it definitely was not located). Both Kohistan-Ladakh and Lhasa terranes amalgamated with Eurasia prior to the early Cenozoic along the Shyok (northern) and Bangong-Nujiang sutures, respectively. The Late Cretaceous–Eocene Transhimalayan/Gangdese batholith developed above the continental convergent margin, which marked the southern edge of Eurasia and is bounded by the Indus–Yarlung Tsangpo suture along its southern margin [*Ahmad et al.*, 2005]. The fifth point is now much better understood following almost 3 decades of intensive research along the India-Asia suture zone in southern Tibet [*Aitchison et al.*, 2000, 2002; *Aitchison and Davis*, 2004; *Davis et al.*, 2002]; the sixth point can be deduced principally from the age dating of calc-alkaline volcanic rocks erupted onto the southern Lhasa block, indicating a continuation of subduction-related activity well into the late Eocene [*Chung et al.*, 2005; *Miller et al.*, 2000], and the oft-cited classic constraint [e.g., *Searle et al.*, 1987], "the youngest marine sediments," identified from a number of studies as being of late Priabonian (~35 Ma) age [*Aitchison et al.*, 2007; *Li et al.*, 2002; *Li and Wan*, 2003; *Li et al.*, 2000; *Wang et al.*, 2002; *Xu*, 2000; H. Willems, personal communication, 2007]. In their recent *Tectonics* commentary *Searle et al.* [2007, p. 1] reiterated this key issue for determining the timing of continent-continent collision by stating: "We believe that the strongest evidence for timing of the start of India-Asia collision remains the ending of the final marine sedimentation in the suture zone and along the north Indian passive continental margin [*Searle et al.*, 1988, 1990, 1997]." While the youngest sediments may not have been documented from localities in NW India, marine sediments as young as Priabonian are indeed present at localities we have visited in the center of the orogenic system in Tibet [see *Aitchison et al.*, 2007, and references therein].

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[5] From a plate-modeling perspective (i.e., drawing upon the first through fourth points), collision of India with Asia at 55 Ma is impossible, but ~35 Ma is perfectly feasible [see *Aitchison et al.*, 2007, Figure 5], which is consistent with the geological record in the Indus-Yarlung suture zone. The fifth and sixth points (principally geological studies of the suture zone rocks with additional constraints provided by seismic tomography [*Van der Voo et al.*, 1999]) tell us that the ~55 Ma event was a Taiwan-style arc-continent collision, with India playing a role analogous to that of the present SE margin of China, which in essence is colliding with and being overridden by, albeit in a geologically temporary configuration, the Luzon arc.

[6] To emphasize the robustness of our model, we draw attention to the fact that for India to have collided with Tibet, part of Asia at ~55 Ma would require a major modification to one or more of the key plate-modeling and suture zone parameters (see above). Perhaps the most flexibility we can offer adherents of the 55 Ma collision model is to suggest the development of a model with a massively distended Greater Asia (second point). However, following collision, there would have to have been an enormous amount of sideways extrusion and/or shortening across Tibet (principally the Lhasa terrane) to "remove" a crustal block or blocks very roughly 2.5×10^6 km^2 in area, for which no evidence exists. Incidentally, prior to the collision the protuberance would need to have had effectively the same E-W width as northern Greater India, again, a quite unlikely scenario requiring special pleading.

[7] Evidence of a 55 Ma collision between an intra-oceanic island arc and India is supported by the geological record. Paleontological evidence from Tibet clearly indicates that marine conditions persisted between India and Asia until almost the end of the late Eocene. Further geological evidence, in particular the sedimentary record, points to a second, more significant collision event and the elimination of oceanic space between India and Asia at that time. Thus, applying *Searle et al.*'s [2007] primary criterion, continent-continent collision must postdate these sediments.

[8] We do not dispute E. Garzanti's earlier (1980s) data, instead preferring to build on his work. The past quarter century has seen many new studies, particularly in areas of southern Tibet where access was previously more difficult. Indiscriminant grouping of geological information potentially attributable to more than one collision event does not necessarily provide the best answer. New data and enhanced stratigraphic resolution permit recognition of two major events separated by ~20 Ma, the latter of which occurred around the Eocene-Oligocene boundary when tectonic modeling predicts India and Asia had converged. We hypothesize that this event is the India-Asia collision in a strict sense. Our new hypothesis is consistent with presently available data and is entirely testable.

[9] Clearly, continent-continent (India-Asia) collision is precluded at 55 Ma, and available constraints serve to falsify the existing hypothesis. We contend that recognition of late continental collision is a major advance in understanding of the India-Asia collision system. Regardless of tests of the ~35 Ma interpretation, as the 55 Ma continent-continent collision hypothesis has already been falsified, this can no longer serve as a "fallback" position. We are not aware of any reason to suspect that Tethys differed markedly from modern ocean basins and to suggest that it likely also contained numerous positive bathymetric features such as intraoceanic island arcs, plateaux, etc. Given the nature of large ocean basins it would come as little surprise if further study of the Himalayan-Tibet orogenic system were to reveal other collision events affecting either the southern margin of Asia or the northern margin of India.

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