Unfeasible subduction?

To the Editor — Subduction of continental crust is generally thought to be inhibited by buoyancy, whereas cooled oceanic crust is denser than the mantle and is prone to subduction[1]. This explains why continental crust is up to billions of years old, whereas in-situ oceanic crust is not more than hundreds of millions of years old. Recently, Ingalls et al.[2] posited that all crust consumed by convergence between India and Asia since about 56 million years ago was continental. They compared modern crustal volumes in the India–Asia collision zone with pre-collisional volumes inferred from their palaeogeographic reconstruction and argued that 50% of this continental crust — a region stretching northward for about 2,400 km, forming a Greater Indian continental promontory — has entirely subducted.

Geophysical modelling suggests that lower continental crust can subduct when the more buoyant upper crust is scraped off (accreted in orogens) and thus escapes subduction[3]. The Himalaya contains accreted continental upper crust that stretches from north to south for less than about 1,000 km when restored to its undeformed state[4]. Thus, according to Ingalls and colleagues' reconstruction[2], at least 1,400 km of Greater Indian continental crust, covering an area similar to Arabia, subducted (mostly before 50 million years ago) at reconstructed subduction rates of up to 18 cm per year[5]. Such a scenario would be extraordinary.

Rapid subduction of large volumes of continental crust challenges both of the ideas that the negative buoyancy of the down-going plate (slab pull) drives plate tectonics, and that continental crustal buoyancy precludes wholesale subduction. This illustrates the importance of kinematic restorations of Greater India. In the absence of an accreted record, such restorations rely on circumstantial quantitative data (such as from palaeomagnetism and plate kinematics) that we suggest favour an alternative geodynamically simpler solution. Different marine magnetic anomaly patterns north and south of the Wallaby fracture zone offshore from western Australia imply that the oceanic crust formed to the north of this fracture zone was formed adjacent to a different plate than that which formed to the south[6]. This implies that in Early Cretaceous time, Greater India was about 800km wide[6]. Such a configuration can be tested using palaeomagnetic data compilations[7,8] from the Tibetan Himalaya. Palaeomagnetic data that pass existing reliability tests[7,9] scatter around the palaeolatitude curve predicted by an 800-km-wide Greater India. In contrast, these palaeomagnetic data consistently plot south of the palaeolatitudes predicted if Greater India is assumed to be 2,400 km wide in Early Cretaceous and older times (Fig. 1).

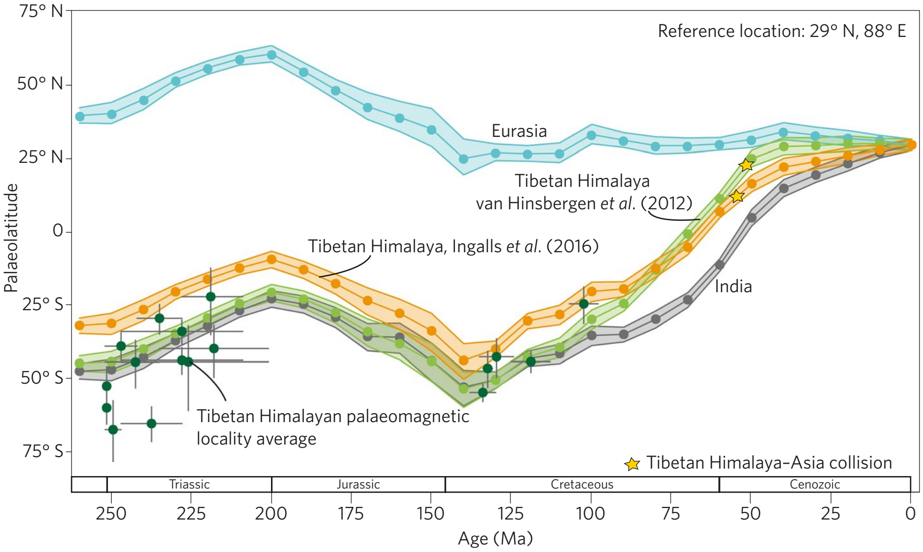

Fig. 1 | Palaeolatitude versus time curve displaying the predicted palaeolatitudes and 95% confidence envelopes for a reference point at 29° N, 88° E using the same global apparent polar wander path as in ref [6]. The curves show the palaeolatitudes predicted for the reference point if that point was rigidly attached to India (grey curve), Eurasia (blue curve), and the Tibetan Himalaya in the scenario of van Hinsbergen et al.[7] (green curve) and Ingalls et al.[2] (orange curve). Palaeomagnetic data of the Tibetan Himalaya[7,8] are indicated with green dots. Figure adapted from ref. [7], National Academy of Sciences.

A narrow Early Cretaceous Greater India and an India–Asia collision age of 56 million years ago require that an ocean basin, similar in size to its entirely subducted area[7,8], opened within Greater India in the Late Cretaceous. Ultramafic detritus in Eocene sediments in the Lesser Himalaya has been correlated to ophiolites overlying the Tibetan Himalaya[10]. This would tie the Tibetan and Lesser Himalaya together with a contiguous continental corridor and preclude a major oceanic Greater India Basin[10]. However, the Upper-Cretaceous2–Eocene Pakistan–Afghan orogen in western India, which formed at the India–Arabia plate boundary, also contains ophiolites[11]. This region may have provided the source for the Lesser Himalayan Eocene ultramafic detritus and, if so, permits a Greater India Basin. Furthermore, although an accretionary oceanic record is lacking in the Himalaya, we note that thousands of kilometres of oceanic lithosphere has subducted beneath South America during the Cenozoic without accretion[12].

We suggest that an India–Asia mass balance calculation may be more rigorous if it uses an approximately 800-km-wide dimension for Greater India during the Early Cretaceous as the maximum estimate for the volume of continental crust[13]. Using this estimate, some continental lower crustal subduction is permissible (as required by geophysical images of the mantle beneath Tibet[14]), but most of the original upper crust resides in the Himalaya[4] or Bengal and Indus fans[15]. The scale of continental subduction in this scenario is closer to that inferred from collisional orogens in Norway, South China and northern Australia[16].

We conclude that the palaeogeographic scenario of Ingalls and colleagues[2], and the associated spectacular geodynamic consequences, even if physically feasible, are not independently supported or required by presently available kinematic data. Instead wholesale subduction of dominantly oceanic lithosphere does satisfy kinematic constraints and is geodynamically more straightforward than large-scale, wholesale continental subduction. ☐

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Reply to 'Unfeasible subduction?'

Rowley and Ingalls reply — The physics of subduction is dictated by the relative densities of crustal materials to the density of the asthenosphere. Crust that has undergone eclogite facies metamorphism has densities exceeding those of the asthenosphere and is continuously subductable. This physical mechanism could account for the loss of crust in the India–Asia collision, and is supported by tomographic images that are interpreted to reveal a thick (about 19 km, approximately half the thickness of the incoming Indian crust) layer of eclogitized lower crust[1], subducted into the mantle beneath the Himalaya during only the last 10 million years or less of convergence[2].

Palaeoaltimetry data[3,4] indicate that southern Tibet has been elevated (more than 4 km) since at least 55 million years ago. This equates to more than 60-km-thick continental crust, sufficient to support continuous production of eclogites within the Himalayan core — and beneath at least southern Tibet — throughout the orogen's collision history. This source of negative buoyancy could contribute to ongoing post-collisional convergence between India and Asia. Eclogites in Tso Morari[5,6] and Kaghan Valley[7,8] demonstrate that upper-crustal eclogites were produced during early collision. The fraction of exhumed relative to subducted upper crustal eclogite is unknown. It is possible that considerable volumes of upper-crustal eclogites were permanently subducted into the mantle during rapid convergence (more than 150 km per million years) early in the collision. This has yet to be constrained by existing data.

In our mass-balance calculations, we cite an erosional volume of $5\pm1\times10^7$ km^3 from the India–Asia collision. Virtually all of this material derives from upper-crustal sources. This volume is equivalent to about 1,400 ± 300 km of upper-crustal convergence, if it is partitioned over a domain with a width of about 2,000 km and thickness of 18 km. About 1,400 km of upper-crustal convergence — plus the approximately 1,000 km of shortening reconstructed from preserved structures within the Himalayas[9] — contribute to a total upper-crustal shortening of about 2,400 km. Subduction of the corresponding eclogitized lower crust thus yields a reasonable mass balance of this system.

Regarding differences in magnetic anomaly patterns north and south of the Wallaby Fracture Zone, it has long been recognized that the opening history of basins off the west coast of Australia is complicated. Several ridge jumps occurred in this region throughout the Cretaceous[10] (see Supplementary Section 1). This variability is responsible for the differences in magnetic anomaly data that van Hinsbergen and colleagues cite as evidence against our interpretation. Furthermore, the magnetic anomalies and early mid-ocean ridge spreading in this region are well modelled[10] with only two plates — Greater India and Neo-Tethys to the west and Australia to the east — just as we argued.

The proposal of an oceanic Greater Indian Basin[11] was based on palaeomagnetic data that have since been dismissed[12]. There is also no geological evidence[13,14] supporting this hypothesis. Early Cretaceous palaeomagnetic data used to infer a limited palaeogeographic source region, within about 800 km of cratonic India, all came from the southernmost edge of the Tethyan Himalaya; the most proximal part. These data cannot constrain the northern margin of Greater India during the Cretaceous or at any younger time, and have no bearing on the hypothetical Greater Indian Basin.

In their comment, van Hinsbergen and colleagues mischaracterize existing provenance arguments (see Supplementary Section 2). Indeed, provenance data have been used to argue against the Greater Indian Basin hypothesis. Detrital zircon data from Eocene clastics of the Lesser Himalaya indicate a Tethyan Himalayan source[15]. These data are incompatible with the Greater Indian Basin hypothesis, which suggests the Lesser Himalaya would have been separated from Tethyan Himalayan sources by an approximately 2,600-km-wide ocean basin in the mid-Eocene. Plus, the ophiolites of central Pakistan were obducted by the Palaeocene[16] and buried by the early Eocene[17], so cannot be the source of early-to-middle Eocene ophiolitic detritus.

Finally, we note that although there is no accretionary prism along the Andean margin of South America despite thousands of kilometres of subduction, the record of Andean arc magmatism is the hallmark of this history. The absence of a subduction-associated magmatic record places the putative Greater Indian Basin in stark contrast with the geologic history of South America. In our view, there is a growing body of data that increasingly support our interpretation involving an expansive Greater India and large-scale subduction of mostly lower continental crust into the mantle during the India–Asia collision. ☐

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