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India–Asia convergence driven by the subduction of the Greater Indian continent

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The most spectacular example of a plate convergence event on Earth is the motion of the Indian plate towards Eurasia at speeds in excess of 18 cm yr^{-1} (ref. 1), and the subsequent collision. Continental buoyancy usually stalls subduction shortly after collision, as is seen in most sections of the Alpine–Himalayan chain. However, in the Indian section of this chain, plate velocities were merely reduced by a factor of about three when the Indian continental margin impinged on the Eurasian trench about 50 million years ago. Plate convergence, accompanied by Eurasian indentation, persisted throughout the Cenozoic era[1–3], suggesting that the driving forces of convergence did not vanish on continental collision. Here we estimate the density of the Greater Indian continent, after its upper crust is scraped off at the Himalayan front, and find that the continental plate is readily subductable. Using numerical models, we show that subduction of such a dense continent reduces convergence by a factor similar to that observed. In addition, an imbalance between ridge push and slab pull can develop and cause trench advance and indentation. We conclude that the subduction of the dense Indian continental slab provides a significant driving force for the current India–Asia convergence and explains the documented evolution of plate velocities following continental collision.

Many authors have suggested that some Indian continental lithosphere has subducted, but owing to its buoyancy has underplated the Asian continent[4,5]. More recently, tomographic imaging of the mantle underneath India has indicated continental subduction to larger depths[6,7]. Reconstructions based on this evidence have proposed that 600–1,000 km of the Indian continental margin was pulled into the mantle, behind the sinking Tethyan oceanic lithosphere[3,7,8], where it partly detached once it reached mid-mantle depths[7,8].

As the entrained continental lithosphere is generally considered too buoyant to actively drive further subduction, an external forcing at the plate's boundaries, possibly provided by the Indian Ocean ridge push[9] or by the pull of neighbouring slabs[10], has been invoked to explain continued continental collision at current rates. We postulate here that the subducting Indian lithosphere, imaged in the upper mantle, has the negative buoyancy needed to sustain subduction regardless of its attachment to Tethys lithosphere. This explains continued collision without the need for forces external to the subducting Indian plate.

The Indian lithosphere facing the Tethys Ocean was typical of thinned continental margins and extended 600–1,000 km north of the present location of India[11]. Quantitative backstripping of Zanskar Range units[12], which represent the most complete transect through this ancient margin[11], constrains the structure of the lithosphere, with a recovered crustal thickness of ∼25 km overlying a lithospheric mantle ∼70 km thick (see the Methods section). The tectonic units accreted in the Himalayas represent 10–20 km of the thickness of the Greater Indian crust[2]. Consequently, only 5–15 km of the lower crust remained to be entrained into the subduction zone and into the mantle. This Indian lower crust has been imaged at depth, following the dipping lithosphere below the Himalayas[13], and has previously been proposed to have sunk into the mantle[2,14,15].

If the subducted continental lithosphere includes a slightly stretched Indian lower crust with an estimated thickness of 12.5 km (labelled Continental margin—LC only, Greater India), then its total average density is denser than the mantle (-12 kg m^{-3}, Methods section). If part of the lower crust is also scraped off and incorporated in the orogen, the downgoing plate density is further increased. In contrast, for the case of a continental lithosphere with an unstretched lower crust of 15 km, the density difference decreases ($+6$ kg m^{-3}), and if the upper crust is not scraped off the top and accompanies the subducting plate instead, the average density will be much lower than that of the mantle ($+100$ kg m^{-3}).

This shows that a continental lithosphere may be denser than the underlying mantle and conducive to subduction[16], provided that it is stretched and part of the buoyant crust is removed[9,16]. Furthermore, the density, temperature distribution and thermal thickness of the remaining subcontinental lithosphere will be very similar to those of a mature oceanic plate, which makes it difficult to distinguish from the oceanic lithosphere in the seismic tomography.

The buoyancy estimates are used to investigate, in a numerical model, the fate of a continent arriving at a subduction zone, to test whether continental subduction is possible, and if so whether it could control the dynamics of the India–Asia convergence. In our models, the subducting plate is divided into two domains, where the buoyancy is modified to reproduce those of a mature Tethys-type oceanic lithosphere and of a continent (Figs 1 and 2a, inset). In the subduction models, velocities emerge self-consistently and evolve in response to the balance of the buoyancy forces and the viscous resistance of the mantle[17], thus differing from previous models of collision[9] and indentation[18,19] where motion is prescribed.

The extent to which a continent can be subducted depends essentially on its buoyancy. The models show that once the oceanic plate is completely consumed, the continental lithosphere that includes the light upper crust is dragged into the mantle to depths of ∼200 km, before stalling subduction and plate motion. In models where the upper crust has been scraped off at the margin, the underlying continent can be dragged to very large depths (∼500 km), eventually jamming subduction. However, if the lower crust is slightly thinned, as is the case for passive margins, the negative buoyancy of the continent, without its upper crust, is enough to lead to slow, continuous subduction (Figs 1a and 2a).

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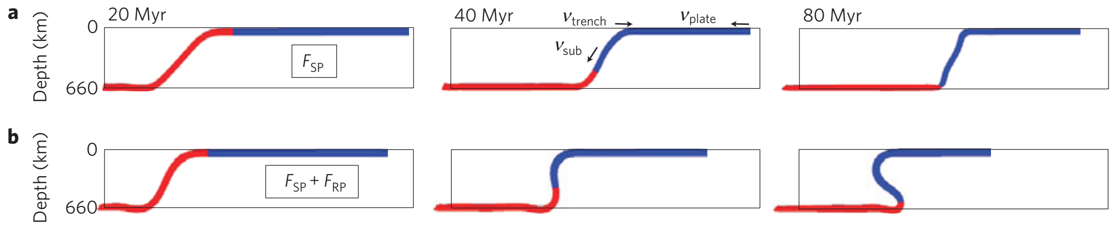

Figure 1 | Evolution of the numerical subduction models. The continent (blue, Continental margin—LC only, Greater India) follows the oceanic plate (red) into subduction. **a**, Slab-pull-driven subduction (F_{SP}). Velocities of subduction (v_{sub}), plate advance (v_{plate}) and trench retreat (v_{trench}) are driven by slab pull and decrease when the continent is subducted. Continent subduction is continuous, although slower, and the slab becomes subvertical. **b**, Slab-pull- and ridge-push-driven subduction ($F_{SP}+F_{RP}$). After the continent starts subducting, subduction slows down (at 40 Myr), the slab steepens, and eventually overturns, under increasing trench advance (at 80 Myr). The depth of 660 km equals that of the upper mantle. There is no vertical exaggeration.

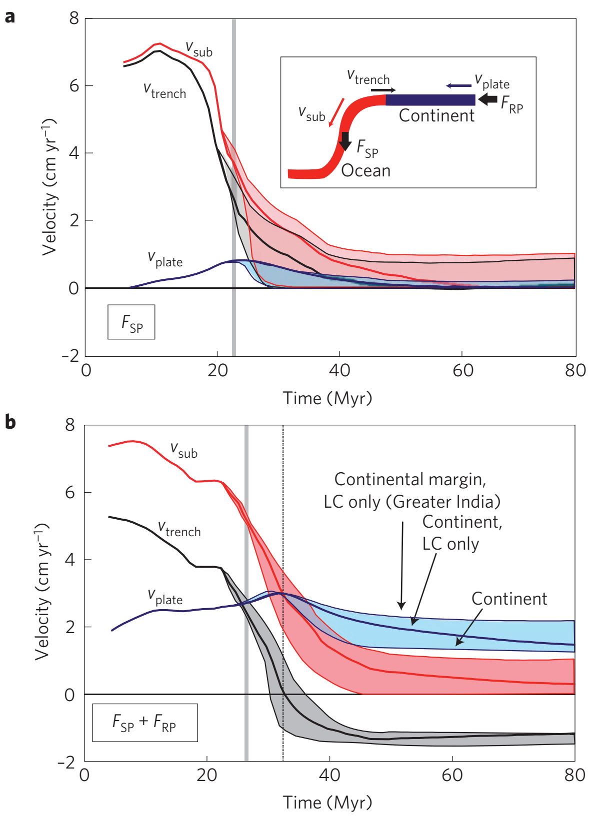

Figure 2 | Velocities of numerical subduction models. a, Slab-pull-driven subduction (F_{SP}). Subduction, trench and plate motions decrease with decreasing pull as the continent is subducted (vertical grey thick line). **b**, Slab-pull- and ridge-push-driven subduction ($F_{SP}+F_{RP}$). Subduction motions are very similar to slab-pull-only-driven subduction. Convergence rearranges significantly on continent subduction (vertical grey thick line): subduction rates decrease below the ridge-push-driven plate and trench motions, and the system progressively switches to a strong trench advance mode marked by the change in sign of v_{trench} (dashed line).

We also tested whether including a trenchward force, of a magnitude expected for ridge push (Supplementary Information) behind the continental plate's tail has an effect on the system. However, the depth of continental subduction does not vary. In other words, forcing at the ridge cannot force the sinking of slabs into the mantle; it only increases plate velocities towards the trench (Figs 1b and 2b). The same behaviour is observed when varying the viscosity at the base of the plate in the asthenosphere. It leads to variable contributions of trench retreat and plate advance, but does not alter the amount of continent subduction. In models that include ridge push, slab pull controls the rate at which the lithosphere is pulled into the mantle, whereas ridge push determines the rate at which the plate is fed to the trench. When slab pull is lowered to values below those of ridge push, as a result of continent entrainment in the mantle, subduction is unable to consume the incoming plate, resulting in trench advance (Fig. 1a).

These results offer the key to interpreting the India–Asia convergence rates in terms of the magnitude and nature of the driving and resisting forces. The most prominent feature of the India–Asia convergence is the threefold velocity drop observed after Tethys closure (Fig. 3), as constrained by the Indian Ocean spreading rates from one of the most recent compilations[20]. This requires a significant change in the balance of forces from before to after collision. The density difference between the subducting oceanic plate and Indian-type continent is the most obvious change that could account for this difference.

Our models with a negatively buoyant continent reproduce such a convergence evolution (Fig. 3), as well as providing a subduction to trench-advance ratio comparable to those provided by estimates of Cenozoic orogenic shortening in the Himalayas and indentation of the Asian plate[2,3]. This suggests that the bulk of the Greater India continental lithosphere is denser than the underlying mantle and that it is now subducting below the collision.

We show that different combinations of surface motions (v_{plate} and v_{trench}) are possible, still leaving continent subduction unaffected. This implies that to achieve a convergence such as that documented[20], Tethys subduction must have occurred by plate advance alone ($v_{plate} \approx v_{sub}$, Fig. 3, dashed lines), allowing only for minor trench migration before collision.

The convergence history can be matched by the models if Greater India continental subduction initiates ~50 million years (Myr) ago, in agreement with geological and palaeomagnetic evidence[21,22]. Following the subduction of the less dense continent, ridge push becomes more significant than slab pull, and plate accommodation partially occurs by trench advance. This implies that indentation of the Asian plate did not start immediately on collision, but was delayed until a substantial amount of continental subduction had reduced the pull force to less than the ridge push. We relate it to when trench motion becomes advancing in our models, ~40 Myr ago. This is in agreement with the geological record of extrusion tectonics in Asia[23], and the oldest Tibetan uplift documented[24]. Models that include a realistic ridge push and subduction in the upper mantle show a large amount of margin migration, eventually overriding the deep slab (Fig. 1b). This is consistent with the location and morphology of the fast slab anomaly at depths imaged by tomography[7].

At the subduction rates estimated, a 600–1,000-km-wide Greater Indian margin could have been entirely consumed, at the latest by ~20 Myr ago. In this case, our models indicate that the subsequent entrainment of the thicker and more buoyant Indian lithosphere, whether or not this includes its upper crust, would result in a

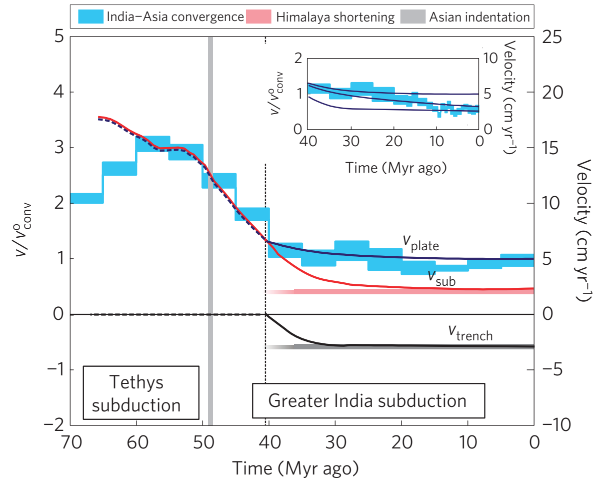

Figure 3 | Comparison of model velocities and India–Asia plate motions. Convergence is constrained by plate kinematics[20]. The collision and trench margin from Himalayan shortening[3] and Asian indentation[3] are on the right axis. Model motions are scaled to a terminal velocity $v_0 = 2$ cm yr^{-1}. The model plate advance v_{ad}, subduction velocity v_{sub} and trench migration v_{trench} are from model 'Continental margin, LC only (Greater India)' of Fig. 2b. The grey vertical line indicates the model's continent entrainment. Inset: v_{ad} curves from the three models in Fig. 2b and plate convergence from 17–0 Myr ago from ref. 25.

further reduction of convergence (up to 50%, Fig. 3, inset) and increased stress propagation to the Asian plate. This offers an explanation for the reduction of the convergence rate and the renewed Tibetan plateau outer growth that possibly occurred by ∼20–10 Myr ago[25].

The trenchward force at the continental plate's tail in our models is consistent with the estimated push of the Indian Ocean ridge[26], suggesting that extra forcing to the Indian plate from neighbouring subduction zones[10] could have been only minor, as it would induce larger relative trench migration than observed. Similarly, a minor role is inferred to a lower viscosity in the Indian asthenosphere, possibly caused by the Deccan plume[27], as this would yield indentation/sinking motion ratios incompatible with the documented velocity evolution.

Although the evolution of the convergence velocities of our models follows a similar pattern to the natural system, the absolute velocities of the India–Asia convergence are, throughout the whole evolution, a factor of ∼2.5 larger than those of our models (Fig. 3). The India–Asia convergence velocities are also a factor of 2–3 higher than most observed Cenozoic motions for the Pacific and Indian Ocean plates[20], which our models, with similar parameter values, do reproduce[28].

The buoyancy forces used here are close to a realistic upper bound of ridge push and upper-mantle slab pull. Faster velocities, while preserving the relative change in convergence velocity, are possible only if the effective regional mantle drag is lower than modelled. An extra driving force, owing to lower mantle slab penetration, has been invoked to explain periods in which Cenozoic motions of several Pacific subduction zones were excessively high for the very young age of attached slabs[28]. Likewise, a lower mantle buoyancy source has been proposed to have maintained Laurentia and Baltica plate drifts in excess of 20 cm yr^{-1} during the Late Precambrian/early Palaeozoic time[29]. Therefore, it seems most plausible that the high velocities of the India–Asia convergence are also a response to a forcing related to lower mantle suction[29,30], sustained by the sinking of the (tomographically well-imaged) Tethys slab in the lower mantle, effectively lowering the resistive drag and increasing the plate velocity[30]. This was initiated by the Late Cretaceous/Early Tertiary[7], at the time the convergence rate increase occurred (Fig. 3).

We demonstrated that the extended Greater India margin, stripped of its upper crust, would have a density higher than the underlying mantle. Such a continental slab, when subducted, will decelerate the motion of India but not stall the process, explaining the current northward motion of India. This suggests that Greater Indian continent subduction exerts an important control on the Meso-Cenozoic dynamics of collision and indentation during the India–Asia convergence.

Methods

The numerical model is as discussed in ref. 17 with parameters detailed in the Supplementary Information. We detail below how the buoyancy used to model the Indian continental lithosphere was derived. The buoyancy of the continental lithosphere, that is, its density contrast times the thickness, is the average of the buoyancy of a plate that includes a lithospheric mantle, a lower and an upper crust. In our models, this is scaled to that of a constant-thickness plate model of 80 km, such that

$$(\rho_{UC}-\rho_{UM})h_{UC}+(\rho_{LC}-\rho_{UM})h_{LC}+(\rho_{L}-\rho_{UM})h_{L}=(\rho_{model}-\rho_{UM})h_{model}$$

where ρ and h, are the density and thickness of different layers such as the upper crust (UC), lower crust (LC), lithospheric mantle (L) and upper mantle (UM). Choosing a thickness for the model, $h_{model} = 80$ km, we find the density ρ_{model}.

The densities used are very standard values, taken from ref. 16. The upper crust density is $\rho_{UC} = 2{,}750$ kg m^{-3}, whereas the lower crust density is $\rho_{LC} = 2{,}800$ kg m^{-3}, which is an average between a diabasic and a granodioritic lower crust. Lithospheric mantle and asthenospheric mantle densities are $\rho_L = 3{,}300$ kg m^{-3} and $\rho_{UM} = 3{,}230$ kg m^{-3}, respectively. We do not include here any densification owing to metamorphism of crustal units. The thickness of the unstretched continent is a total of 100 km, which includes $h_{UC} = 15$ km upper crust, $h_{LC} = 15$ km lower crust and $h_L = 70$ km for the lithospheric mantle. The lithospheric mantle thickness is that of a thermally equilibrated continent ∼40 Myr after the stretching event. This same thickness is used for the Greater Indian margin, because the lag between margin formation and subduction is >40 Myr. For the model plate buoyancy, we have used a crustal thickness, for both upper and lower crusts, of 12.5 km, as constrained by the stretching $\beta = 1.2$, recovered from the Zanskar units[12], of an initially 30-km-thick crust.

With the parameters chosen, we obtain a scaled density for the thick buoyant continent model of +100 kg m^{-3}, referred to as Continent; for the same continent stripped of its upper crust the density contrast is +6 kg m^{-3}, referred to as Continent, LC only. These models resist subduction. If the lower crust of the continent thins by a factor 1.2, referred to as Continental Margin, LC only (Greater India), the scaled average buoyancy is −12 kg m^{-3}, enough to drive slow subduction once entrained in the trench.

The buoyancy of the oceanic lithosphere has been recovered in the same way, where the oceanic gabbroic crust has a density of $\rho_{OC} = 2{,}800$ kg m^{-3} and thickness of $h_{OC} = 8$ km. The density of the oceanic lithospheric mantle is $\rho_{OL} = 3{,}300$ kg m^{-3}, whereas the lithospheric thickness is calculated as a function of the age, here 80 Myr, as $h_{OL} = 2.32\kappa t^{1/2}$, where κ is the thermal conductivity (approximately 10^{-6} m^2 s^{-1}) and t is time in seconds, yielding a thickness of 80 km and a density contrast of −88.75 kg m^{-3}.

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Author contributions

F.A.C. and G.M. designed and carried out the numerical models. F.A.C., G.M., S.G. and L.M. discussed the implications for continental and Indian subduction. F.A.C. and R.F.W. discussed Indian tectonics. All of the authors contributed equally to writing the paper.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to F.A.C.