

What makes India such a good indenter?

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Since about 50 Ma, the ongoing continental collision of India and Asia has led to widespread deformation within Central Asia. A similar pattern results when a rigid indenter pushes into a deformable medium. Therefore, for simplicity, many models have assumed that continental India is rigid. However, in reality, its northern margin has deformed, producing the Himalayan arc and syntaxes. To account for these, we have made physical models containing continental or oceanic plates. For realistic plate configurations and boundary conditions, our models have reproduced the Himalayan arc and syntaxes, as well as the asymmetric distribution of mountain ranges, high plateaus and basins in Central Asia. On this basis, we suggest that two features make India a good indenter. First, the Indian continental crust is buoyant and so resists subduction. Second, the surrounding oceanic crust is mechanically strong. The result is a V-shaped indenter, buoyant in the middle and strong at the sides.

Keywords: Asia, indenter, light continent, strong flanks, syntaxes.

SINCE about 50 Ma, the ongoing continental collision of India and Asia has led to intense deformation along the northern margin of India and throughout much of Central Asia¹. The area is seismically active. Landsat images show crustal thickening, strike-slip faulting and rifting²⁻⁴. Crustal thickening prevails in areas close to the suture between the colliding continents. In the Asian plate there are two large plateaus, Tibet and the Pamirs, as well as a series of mountain ranges, including the Tien Shan and Altay (Figure 1). Further north, strike-slip faulting is prevalent. Finally, rifting dominates in two areas far from the suture, around Lake Baykal in the west and the Ordos block in the east. More generally, at the western edge of deformation, the long Oman–Baykal zone has registered left-lateral motions, transpressional in the south and trans-tensional in the north^{5,6}. Since its separation from other fragments of Gondwana at about 160 Ma, India has drifted NNE over a distance of about 8000 km at an average velocity of about 5 cm/year (ref. 7). The progressive movement of India in the NNE direction, relative to Asia can also be observed in the plates given in the website <http://www.ig.utexas.edu/research/projects/plates/index.htm>. Before its collision with Asia, the primeval continent (Greater

India) was longer in a N–S direction than it is today⁸. Its northern edge was a thin passive margin, a result of previous rifting. Further north was a remnant of oceanic crust, part of the Palaeo-Tethys ocean. To the east and west of Greater India were strips of oceanic crust, which formed part of the Indian plate. Today their remainders extend northward, from the Gulf of Oman or Bay of Bengal, beneath deep-sea fans and deltas^{9,10}, as far as the syntaxes. Following subduction of Palaeo-Tethys beneath continental Asia, the northern margin of India entered into soft collision with Asia. This gave way to hard collision, when more normal continental lithospheres came into contact. Currently, the Indian sub-crustal lithosphere subducts beneath Asia as far as the suture, whereas most of the crust scrapes off, forming the Himalaya¹¹. The current velocity field in Asia and India has been well established in recent years, by analysis of seismic moments¹² and by Global Positioning System (GPS) measurements¹³. The GPS measurements in China indicate that crustal shortening accommodates most of the India's penetration into Eurasia¹⁴ and suggest that deformation within the Tibetan plateau and its margin, the Himalaya, the Altyn Tagh and the Qilian Shan, absorbs more than 90% of the relative motion between the Indian and Eurasian plates. Further, based on the GPS technique under geodetic data constraint the present-day convergence rate of Indian to Eurasia subduction is 21.8 mm/a, with a dipping of 8.1° to the north¹⁵. This is in good agreement with various geological predictions indicating that the convergence rate of the India to Eurasia subduction is stable over a very long time¹⁵.

Ongoing collision is responsible for crustal thickening in Tibet, the Pamirs, the Tien Shan and the Altay, as well

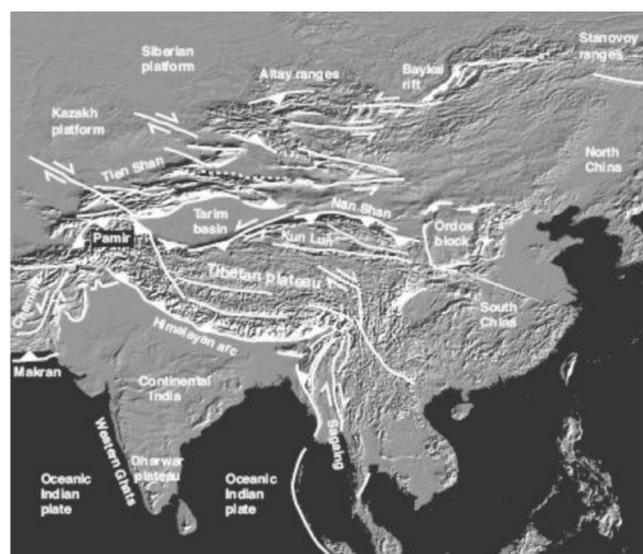


Figure 1. Main Cenozoic structures of Central Asia and India. Shaded relief highlights thickened areas (Tibetan plateau and Pamirs, Tien Shan and Altay ranges), as well as Baykal and Ordos rifts. Western edge of deformation is left-lateral Oman–Baykal wrench zone. Notice high plateau in the southern peninsular India.

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as a significant component of extrusion (about 20%) to the east and southeast. The finite deformation is less well known, although aspects have been elucidated by structural studies, plan-view restoration⁵ and palaeomagnetic studies. For example, rotations of up to 60° have occurred about vertical axes, counter-clockwise along the Oman–Baykal zone¹⁶ and clockwise on the eastern side of Tibet¹⁷. Because the pattern of deformation in Central Asia is so striking, many attempts have been made to model its development. A ready analogy is a rigid indenter pushing into a deformable medium¹⁸. More complete numerical models have focused mainly on crustal thickening and the formation of plateaus^{19,20}. Early physical models appealed to a rigid indenter, explaining the pattern of strike–slip faults in terms of extrusion towards the eastern margin of Asia²¹. More developed physical models were able to account for crustal thickening, strike–slip faulting and rifting²². Allowing for some extrusion, the models resulted in a single plateau, bounded to the west by a long left-lateral shear zone, which is analogous to the Oman–Baykal zone⁵. However these models did not correctly reproduce the pattern of deformation near the suture. Whether physical or numerical, almost all models of the India–Asia collision have assumed that continental India is rigid. However, in reality its northern margin has deformed, producing the Himalayan arc and its two syntaxes²³. The arc itself is almost a perfect small circle²⁴. Palaeomagnetic studies have shown that the arc acquired its curvature as a result of deformation²⁵. The motions on its bounding thrusts are perpendicular to the arc. The syntaxes (Nanga Parbat in the west, Namche Barwa in the east) are areas of intense compressional deformation, where thrust traces are highly curved or even cross-cutting^{26–28}. Shortening has occurred in most horizontal directions, producing large domical folds. Uplift and denudation have been fast, so that crystalline metamorphic rocks of the Indian plate crop out at high elevations. Thus two outstanding questions are what has caused the curvature of the Himalayan arc, and what is responsible for the exceptional deformation in the syntaxes?

To account for the deformation pattern near the suture, we resorted to physical models in which we paid attention to the distribution of continental and oceanic lithospheres and to the boundary conditions on the plates. We assumed that the continental lithosphere consists of three fundamental layers, brittle upper crust, ductile lower crust and viscous lithospheric mantle, whereas the oceanic lithosphere consists of two layers. Underlying the lithosphere is an asthenosphere of much smaller viscosity. Accordingly, our model materials were sand for the brittle crust, two varieties of silicone for the ductile lower crust and lithospheric mantle and honey for the asthenosphere. The modelling technique and its applications to continental collision have been described by many workers^{5,29–35}. However, the current application is novel. The densities and mechanical properties of the model materials ensured

proper dynamic scaling (described later in the text). The models were constructed and deformed in a rectangular tank with rigid sidewalls. The model lithosphere was a mosaic of plates, of oceanic or continental type, representing Asia, India and, in some experiments, Arabia (Figure 2*a*). Oceanic lithosphere was heavier and stronger than continental lithosphere. The Asian lithosphere was continental, except at its eastern margin, where a weak strip of ductile material allowed limited eastward extrusion. The Indian plate consisted of oceanic and continental

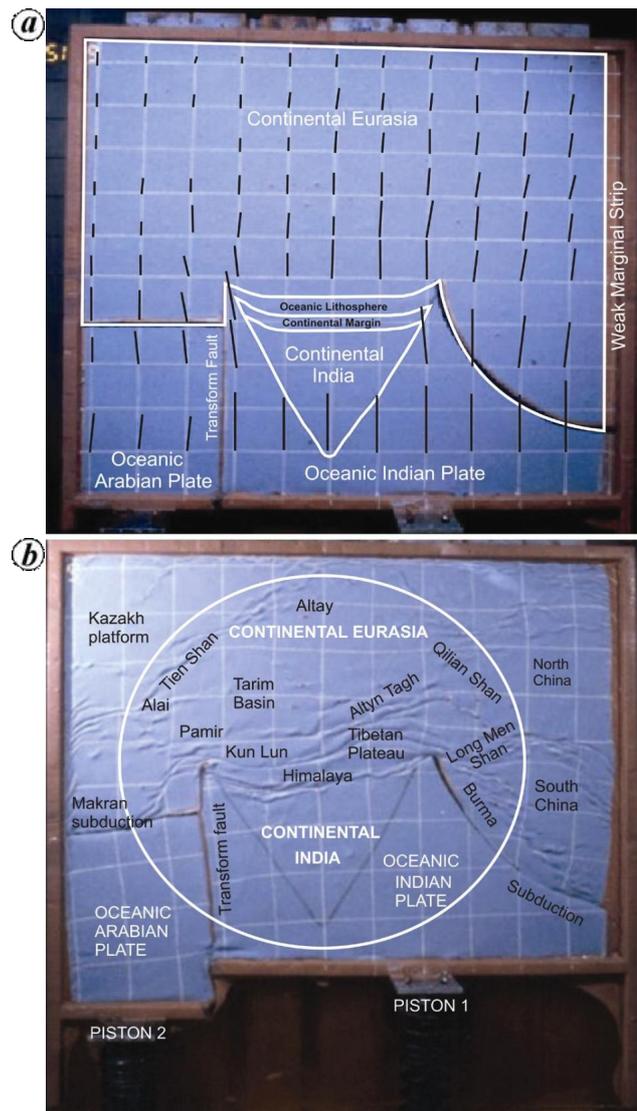


Figure 2. Preferred physical model of indentation (experiment 12). Asian plate was purely continental; Indian plate consisted of continental and oceanic domains, including thin continental margin; Arabian plate was purely oceanic. At the eastern edge of Asia, weak strip allowed some extrusion. *a*, Before deformation notice initial transform fault between Indian and Arabian plates. *b*, Two advancing pistons caused deformation. Oceanic lithosphere subducted beneath continental Asia. Collisions of continental India and Asia led to thrusting of Indian margin in Himalayan arc and syntaxes, and widespread deformation in Central Asia. Area of interest (white circle) is around suture. Vectors (black lines, *a*) indicate total displacements, from undeformed to deformed states.

domains, as in nature. At its northern margin, continental India had a thin, weak strip, equivalent to a passive margin. This abutted a strip of oceanic lithosphere, representing a remnant of the Palaeo-Tethys Ocean. The Arabian plate consisted only of oceanic lithosphere. At the southern edge of the model, two rigid pistons imposed northward displacements, fast for the Indian plate and slow for the Arabian plate. Unfortunately, the size of the box limited the amount of displacement, which was less than the equivalent displacement in nature (described later in the text). Between the Indian and Arabian plates, relative motion occurred on an artificial transform fault. We did 13 experiments, increasing the complexity of the plates and boundary conditions, until the results were realistic. In our preferred model (experiment 12, Figure 2 *b*), oceanic lithosphere of the Indian and Arabian plates subducted beneath continental Asia, until continental India collided. At that stage, but not before, deformation appeared within model Asia and also along the northern margin of India (area in white circle, Figure 2 *b*). In model Asia, deformation was mainly by folding and thrusting. Two plateaus appeared, one larger than the other. In position, size and shape, they resembled Tibet and the Pamirs. Additionally, the weak strip at the eastern edge of the model allowed some eastward extrusion. A left lateral zone in the NW corner of the model resembled the Oman–Baykal zone of Central Asia. A second left-lateral zone on the NW edge of the main plateau resembled the Altyn Tagh Fault. A third zone, right-lateral, formed next to the subducting NE edge of the Indian plate. Its analogue in nature would be the sagging fault zone in Myanmar (Burma). In the western part of model Asia, an area of little or no internal deformation resembled the Tarim basin, which is indeed little deformed in nature. Thus the model reproduced the main structures of Central Asia in terms of location, orientation, style and symmetry. For most structures, deformation was less intense than in nature. However, the amount of indentation was also smaller. The pattern of displacement vectors (black arrows, Figure 2 *a*) was similar to that obtained from GPS measurements in Asia¹³, but less fan-like. For the Indian continent, the model reproduced the Himalayan arc and its two syntaxes. The arc developed within the more deformable marginal strip of continental India. Its curvature resulted from drag at the ends, against the adjacent oceanic lithosphere, which did not deform. The syntaxes wrapped around the prongs of strong oceanic lithosphere, undergoing intense deformation. To test what would happen if the entire Indian continent were weak, we made a model (experiment 13) in which the brittle Indian crust was abnormally light and therefore weak at depth (Figure 3). In this model, as a result of collision, almost all the deformation occurred within continental India. The southern tip thickened by folding and thrusting, whereas the margins slipped in strike-slip mode, left-lateral in the east and right-lateral in the west. Has deformation of this style and intensity

occurred in nature? In the Dharwar plateau of southern India, Precambrian basement rocks reach altitudes of nearly 2700 m, the Moho is as deep as 40 km or more³⁶, large earthquakes have occurred recently on E–W trending thrust faults³⁷, GPS measurements indicate some shortening in a N–S direction³⁸, and there has been significant denudation, possibly in the Cenozoic according to fission-track data³⁹. Although in nature the deformation appears to be much less intense, in style it resembles the model.

In nature, the area of interest is nearly 6000 km². To remain within reasonable limits, we made our laboratory models 1.2 m². In other words, the length ratio was 0.5×10^{-6} . Also for practical reasons, the density ratio was 0.5. To ensure that body forces and surface forces were properly scaled²⁹, the stress ratio was made equal to the product of length and density ratios, i.e. 0.25×10^{-6} . We chose a model viscosity of 1.5×10^4 Pa s for the lower crust and 2.0×10^5 Pa s for the lithospheric mantle, so as to obtain convenient ratios of viscosity (10^{-16}), strain rate (10^{10}) and time (10^{-10}). Assuming that in nature the brittle upper crust fails according to a frictional law, we used two varieties of dry sand as model materials. Representing oceanic crust, sand-1 was an uncemented, well-sorted, quartz sand of eolian origin, from Fontainebleau, France. We sieved it, retaining the fraction below 0.3 mm. The bulk density⁴⁰ was about 1.4 g cm^{-3} . Representing continental crust, sand-2 was a mixture of sand-1 and 20% by weight of ethyl cellulose powder. This mixture had a density of 1.2 g cm^{-3} . As in rocks, shear failure in both sands occurred along narrow zones, where progressive dilation led to localization. In Mohr stress space, both sands had approximately linear Mohr envelopes for initial failure, the angle of internal friction being about 40°. The apparent cohesion was about 500 Pa

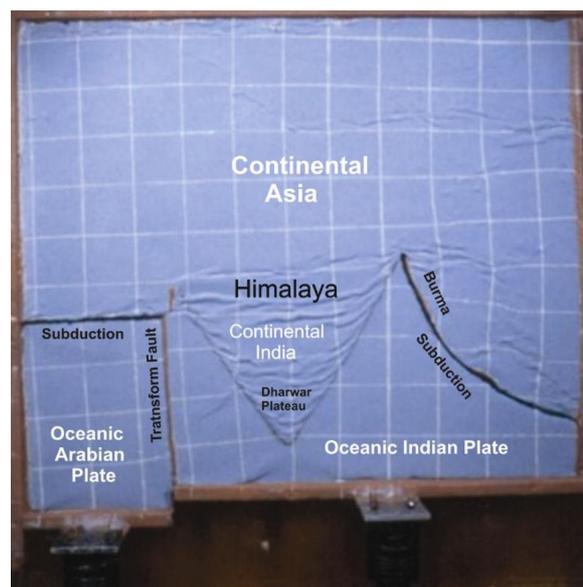


Figure 3. Physical model in which continental India was too weak (experiment 13). Deformation concentrated in continental India, forming folds and thrusts near the southern tip and strike-slip faults at the sides.

for sand-1 and 300 Pa for sand-2 (ref. 40). Representing ductile crust, silicone-1 (Silbione Gomme 7007; Rhône-Poulenc, France) was almost perfectly Newtonian over the experimental range of strain rates. It had a density of 1.2 g cm^{-3} and a viscosity of $1.5 \times 10^4 \text{ Pa s}$. Representing stiff lithospheric mantle, silicone-2 was a mixture of silicone-1 and powdered galena. It had a density of 1.38 g cm^{-3} and a viscosity of $2.0 \times 10^5 \text{ Pa s}$, the mixture being Newtonian. For the mantle asthenosphere, we used a natural clear honey. This material was also Newtonian. It had a viscosity of about 10 Pa s and a density of 1.40 g cm^{-3} . All models were housed in a rectangular transparent box, 120 cm long, 120 cm wide and 30 cm deep. They were built in five steps. (1) The box was filled to a depth of 5 cm with honey. (2) A layer of silicone-2, 1 cm thick and as wide as the box, was pressed in an external mould and then floated onto the honey. (3) A layer of silicone-1 (3 mm thick) was similarly moulded, cut into shapes like continental India or Asia, and laid down in appropriate positions over silicone-2. (4) Layers of sand-1 (5 mm thick) or sand-2 (3 mm thick) were deposited from a hopper, spanning the model. Templates restricted the sand to a specific area. (5) In some experiments, continental India had a weak northern marginal strip comprising a layer of silicone-1 (1 mm thick) within sand-1. In general, the boundaries between oceanic and continental lithosphere were coherent. Some of them later faulted, becoming subduction zones or transform faults. In some experiments, the rate of subduction was increased by adding powdered galena at the surface. To initiate transform faults between contiguous oceanic plates, we removed a narrow strip of sand, using a vacuum cleaner fitted with a fine nozzle. Along this strip, the ductile lithospheric mantle rose isostatically to the surface, providing a zone of weakness. In all experiments, the northern and western boundaries of the models were stationary. Viscous layers were in coherent unlubricated contact with the side plates of the box and sand layers were in frictional contact with them. Next to the fixed eastern side plate was a strip, 5 cm wide, where the model lithosphere consisted of a single layer of silicone-1, 1 cm thick. This artificial strip allowed limited eastward extrusion. At the southern boundaries of the models, pistons moved northward, displacing lithospheric plates. Computer-controlled stepping motors provided steady velocities. For models with two tectonic plates, a single piston, as wide as the entire model, advanced northwards at 2 cm/h. For models with three plates, we used either one piston (at 5 cm/h) over part of the southern boundary, or two pistons (at 3 and 5 cm/h), over adjacent segments. The pistons had vertical edges, deep enough to push the model lithosphere, but not the honey. In no experiment did we allow the piston displacement to exceed 15 cm (equivalent to 750 km in nature), because the subducting Indian plate then touched the bottom of the box, modifying the force distribution. We used a camera with a pro-

grammable back for time-lapse photography of the upper surfaces. The photographs revealed the changing shapes of surface grids, plate boundaries and continental edges, as well as fault traces. Oblique lighting provided semi-quantitative information on surface relief. Occasional photographs through the transparent side-plates and bottom of the box provided additional information on crustal and lithospheric thicknesses. At the end of each experiment, the sand layer was stripped off using a commercial vacuum cleaner fitted with a fine nozzle. Stripping revealed the upper surface of the silicone, representing the brittle–ductile transition in nature.

Our preferred model reproduced the Himalayan arc and syntaxes, as well as the asymmetric distribution of mountain ranges, high plateaus and basins in Central Asia. We believe that this similarity resulted from an adequate choice of plate configurations, lithospheric properties and boundary conditions. Compared to most previous models, ours did not assume that continental India was a rigid indenter. Instead we assumed that continental India was deformable as Asia. However, the model took into account the oceanic lithosphere, which was indeed stronger in compression. Although the boundary displacements were smaller than in nature, the pattern of structures was similar to that observed in Asia and India today. This suggests that the pattern may have become established in the early Tertiary, soon after the onset of collision, and that it has not changed significantly since then. On the basis of our experiments and their similarity with nature, we suggest that two features make India a good indenter. First, the Indian continental crust is buoyant and remains at the surface, even though its sub-crustal lithosphere subducts. Second, the surrounding oceanic crust is mechanically resistant to horizontal compression. The result is a V-shaped indenter, buoyant in the middle, and strong at the sides. The prongs do the indenting, while the buoyant continent stops them from subducting. Away from continental India, the oceanic lithosphere is also strong, but it is heavy enough to subduct, and therefore does not indent continental Asia. A V-shaped indenter may explain the uniform curvature of the Himalayan arc. If we assume that the lithosphere is a Newtonian fluid, flowing between two parallel walls (Couette flow), the velocity profile is a parabola. For small deformation of an initially straight mountain front, the curvature is the second derivative of the velocity profile; in other words, a constant. More realistically, the depth-integrated flow law of the lithosphere, whether in our model or in nature, is not Newtonian. Therefore, our prediction is not strictly valid. However, it provides a first approximation. The curvature of the Himalayan arc may be accentuated in nature by southwards thermal collapse of a thickened Tibetan plateau. One of the limitations of our physical model is that it cannot account for such thermal readjustments. To conclude, if our arguments are correct, small continents should make good indenters. The idea is

hard to test empirically, because India appears to be the only current example on Earth. Perhaps a careful look at the geological record will provide other examples of small but efficient indenters that operated in the past.

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