TECTONICS

Sinking continents

The sequence of events during the collision between India and Eurasia has long been contested. Numerical simulations imply that the key to the puzzle could lie in the subduction of continental lithosphere.

R. Dietmar Müller

Despite more than 150 years of research on the topic, the evolution of the Himalayan orogen remains an enigma. Yet Tibet may hold the key to unravelling what gives the Earth its tectonic pulse. The hidden shreds of evidence narrating Tibet's geological history span deep ocean basins, continental margins, rivers, rugged plateaux, the world's biggest mountain chain and massive sinking and rising blobs of mantle material at great depths in the Earth. Reading these clues requires gathering data in vastly different settings, but a geodynamic simulation is required to understand fully the processes that created Tibet and that continue to ram India into Eurasia, albeit at reduced speed. Writing in *Nature Geoscience*, Fabio Capitanio and colleagues step into this hotly contested arena — a source of collisions of many sorts, including those between geologists, geophysicists and geodynamicists — and explore the evolving tectonic force balance during continent–continent collision using a numerical model[1].

Usually, when two continental plates collide, the movement of the two plates towards each other stops. Most continents are too buoyant to sink into the dense mantle, and the plates therefore remain locked into each other at the surface. However, the India–Eurasia collision is an exception to this rule. About 50 million years (Myr) ago, when the collision may have started, plate velocities decreased by a factor of three. However, they did not vanish entirely. Where the force comes from that continues to push India and Eurasia together is a matter of hot debate. One possibility involves external forces at the boundaries of the Indian plate, for example a push of the plate towards Eurasia exerted by the Indian Ocean ridge.

Capitanio and colleagues[1] use cutting-edge software, the aptly named UNDERWORLD code, to investigate a different possibility. They simulate the thermomechanical evolution of the Indian and Eurasian plates before and during continental collision, and find that the density of continental lithosphere is higher than that of the underlying mantle once the upper crust has been scraped off, as is expected to happen during continental collision. The remaining dense continental lithosphere then sinks into the mantle, dragging the Indian plate with it and promoting continued convergence after collision is well under way.

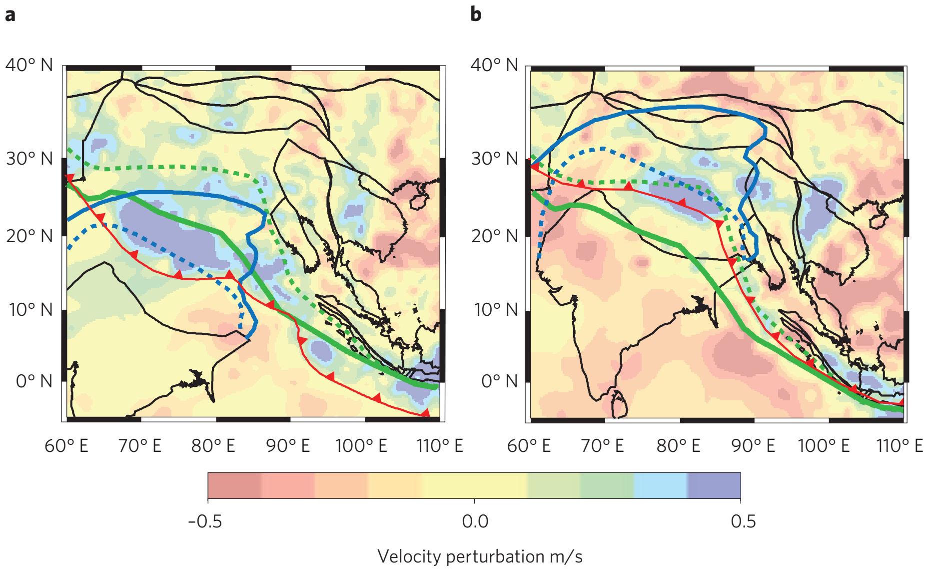

Figure 1 | P-wave mantle tomography[4] roughly linked to reconstruction ages using average slab-sinking velocities[8]. **a**, Reconstruction at a depth of 1,100 km, or about 50 Myr ago. **b**, Reconstruction at a depth of 880 km, or about 31 Myr ago. Reasonable minimum[2] extents (dotted lines) and maximum[9,10] extents (full lines) of Eurasian (green) and Greater Indian (blue) margins are reconstructed for these two time slices on the basis of published rotations[11]. Capitanio and colleagues[1] assume the maximum extent of both the Eurasian and the Indian margins in their model and that the plates collided 55–50 Myr ago (**a**). According to their model, the continental lithosphere (after the crust had been stripped off in collision) was sufficiently dense to sink into the underlying mantle and pull the Indian plate towards Eurasia. Alternatively, continental collision could have occurred as late as 31 Myr ago (**b**) if minimum extents for both plates are assumed. The locations of subduction zones (red) at different times are based on where slabs are imaged in the mantle at different depths/times.

This work illustrates that the sophistication of numerical models has now reached a level where the force balances of colliding plates can be modelled dynamically, using constraints from plate kinematic models and geological observations as boundary conditions and for model validation. Such models have the potential to distil geological and geophysical knowledge into sophisticated process models that allow us to unravel how the Earth's tectonic plates turn flat land into giant mountain chains and deep fault zones. However, the specific results of Capitanio and colleagues[1] depend on the details of the boundary conditions used in their model. They make two critical assumptions: that the collision between Greater India and Eurasia started about 55–50 Myr ago and that the thinned, northern Indian passive continental margin was 600–1,000 km wide.

The timing of the initial collision between Greater India and Eurasia depends strongly on the assumed geometries of the northern Greater Indian and southern Eurasian margins at the time of collision. Neither of these geometries is tightly constrained (Fig. 1). A collision between Greater India and Eurasia as early as 55 Myr ago is plausible under the assumption of a maximum seaward extent for both continental margins (Fig. 1). If instead the minimum estimated seaward extent is used for both margins, the collision is more likely to have occurred around 34 Myr ago[2].

In this case, the subduction of continental lithosphere would have started much later and the event of 55–50 Myr ago would have been caused by India's collision with an oceanic island arc, closing a major ocean basin and leaving only relatively young, buoyant back-arc basin crust to be subducted. The resulting diminished northward pull acting on India since 55–50 Myr ago would be an alternative explanation for India's deceleration at that time. There is ample geological evidence for the existence of intra-oceanic island-arc assemblages in the Himalayan mountains[2], implying the existence of a Cretaceous back-arc basin, which has also been inferred from the distribution of subducted slab material imaged beneath northern India and Tibet[3,4]. There is evidence[4] for a northward migration of subduction after 50 Myr ago (Fig. 1b). The migration of subduction could have been the consequence of the demise of subduction along an intra-oceanic island arc south of a back-arc basin bounding the margin of Eurasia. The system's response to continued convergence would have been subduction north of the back-arc basin. In this scenario, India's collision with Eurasia and the ensuing subduction of continental lithosphere would start about 20–25 Myr later than assumed in the model of Capitanio and colleagues[1], and cause the major slowdown of India–Eurasia convergence speed after 20 Myr ago[5], but without continental lithosphere reaching mid-mantle depths.

Whether or not Greater India had a thinned continental margin 600–1,000 km wide (the second assumption made by Capitanio and colleagues) will no doubt remain contested as well. A margin of these dimensions would be the widest known continental margin anywhere on the Earth, and the possibility seems unlikely: in the Palaeozoic era, two generations of continental slivers rifted away from the northern Gondwana margin, which included the precursor of the Greater Indian plate[6]. These events would have rifted away most of the previously existing thinned continental margin crust. To create an unusually wide margin it is necessary to stretch the continental lithosphere extremely during continental rifting. However, the stretching factor of the northern Indian margin has been estimated to be quite modest[7]. From this point of view, Greater India would not be the place to look for an unusually wide margin.

Capitanio and colleagues[1] have provided a fresh perspective on the long-standing problem of understanding the sequence of events before and after the collision of India and Eurasia, and its traces in today's mantle. However, whether prospecting for continental slabs deep in the Earth's mantle would be successful is likely to remain controversial for some time. ❐

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PALAEOCLIMATE

Extreme iceberg generation exposed

In the North Atlantic region, six massive iceberg discharge events marked the last glacial period. A numerical model now links these events to ocean temperatures and ice-shelf conditions.

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Earth's sedimentary materials, from terrestrial soils to seafloor sediments, contain a wealth of information about past climate states and events. However, these records are often incomplete and difficult to interpret. Widespread episodic deposits of ice-rafted debris that punctuate the sediment record of the glacial North Atlantic Ocean — known as Heinrich layers — have proven tricky to understand. They are attributed to massive iceberg discharge from Northern Hemisphere ice sheets, but the mechanisms leading to the development of the iceberg armadas remain controversial. Writing in *Nature Geoscience*, Alvarez-Solas and colleagues[1] describe a simple model that links ice-sheet and iceberg discharge to fluctuations in ocean temperature, through an ice shelf connected to a fast-flowing stream within the ice sheet.

The last glacial period was characterized by millennial-scale climate oscillations between relatively mild and relatively cold conditions called Dansgaard–Oeschger cycles. These cycles are seen most prominently in Greenland ice cores, but are present in many palaeoclimate records, indicating that these climate swings are global in scale[2–4]. There is as yet no consensus regarding the forcing responsible for Dansgaard–Oeschger cycles, but similar transitions between cold and warm phases can be simulated in ocean models by varying the freshwater flux to the ocean surface.

Six Heinrich layers are apparent through the last glacial, between 70,000 and 14,000 years ago[5–7]. The ice-rafted debris events — known as Heinrich events — coincide with the culminations of sets of increasingly cold Dansgaard–Oeschger cycles. Heinrich events do not occur during every cool phase or with reliable freqency, but the timing of Heinrich-layer deposition is not entirely irregular either: they are always found at the cold extremes. It seems reasonable to conclude that the Dansgaard–Oeschger cycles and Heinrich layers are related, but more interpretive tools are required to understand how they are related.

The production of a Heinrich layer requires three conditions: a sediment source; a mechanism for moving that sediment up into the glacier ice and transporting it safely to the ocean; and a process that varies the rate of dirty iceberg production, or at least the persistence of the icebergs and their debris at sea. This third requirement may be met internally by processes in the ice sheet, or externally by forcing from other components of the climate system.