

Lithospheric Deformation in the equatorial Indian Ocean: Timing and Tibet

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DIFFUSE OCEANIC PLATE BOUNDARY BETWEEN THE INDIAN AND CAPRICORN PLATES

The plate tectonics revolution of the 1960s transformed our understanding of the way our planet works. Since its inception, the main modification to the plate tectonic theory is the recognition that many plate boundaries are not narrow, as originally assumed, but are hundreds to thousands of kilometers wide. These diffuse plate boundaries occur not only in the continents, where they were first recognized, but also in the oceans. The best example of a diffuse oceanic plate boundary occurs in the equatorial Indian Ocean between the Central Indian Ridge and Sumatra trench, where motion between a distinct Indian plate (to the north) and Capricorn plate (to the south) is accommodated (Wiens et al., 1985; Gordon et al., 1990; Royer and Gordon, 1997; Conder and Forsyth, 2001; Gordon et al., 2008) (Fig. 1). This region is a natural laboratory for investigating the driving forces, rheology, and deformation of oceanic lithosphere.

The pole of rotation of the Indian plate relative to the Capricorn plate has been estimated with compact confidence limits and lies near 4°S, 74°E. The pole and associated well-determined rate of rotation tightly limit the displacement rates of assumed rigid Indian lithosphere relative to assumed rigid Capricorn lithosphere (DeMets et al., 1994; Gordon et al., 2008) (Fig. 1). Unlike the poles of rotation for plate pairs separated by a traditional narrow plate boundary, which tend to lie far from the plate boundary, poles of rotation across diffuse oceanic plate boundaries tend to lie within the diffuse boundary itself, thus separating a region of contractional deformation from one of extensional deformation (Gordon, 1998). The pole of rotation between the India and Capricorn plates follows this tendency (Fig. 1). West of the pole of rotation, between the Central Indian Ridge and Chagos Bank, the lithosphere fails by normal and strike-slip faulting (Wiens et al., 1985; DeMets et al., 2005). Just east of the pole of rotation, in the Central Indian Basin, failure is mainly by thrust faulting. Farther eastward, and in the Wharton Basin to the southeast, failure is by a mixture of strike-slip and thrust faulting. Dramatic folds, presumably of the combined brittle and semi-brittle portions of the lithosphere, with wavelengths of 100–300 km, occur in both the Central Indian Basin (Eittreim and Ewing, 1972; Weissel et al.,

1980; McAdoo and Sandwell, 1985) and in the Wharton Basin (Stein et al., 1989; Petroy and Wiens 1989) (Fig. 1).

TIMING

An important question about the India-Capricorn plate boundary is when motion and deformation across the boundary began. Two major unconformities, revealed by an extensive network of seismic profiles, can be traced across the Bengal fan (Curry and Munasinghe, 1989). The age of the younger unconformity coincides with the onset of the folding and associated faulting that continues today. This unconformity, which has been drilled in two places separated by ~1100 km, is 7.5–8.0 Ma old (Curry and Munasinghe, 1989; Cochran, 1990) and dates the onset of lithospheric folding.

TIBETAN CONNECTION

The onset of folding in the equatorial Indian Ocean may coincide with the onset of widespread normal faulting in the Tibetan Plateau at ca. 8 Ma ago, when the plateau was hypothesized, by Harrison et al. (1992) and Molnar et al. (1993), to have first attained an elevation that equals or exceeds its present elevation. The hypothesized attainment of maximum elevation may in turn be related to significant climate change at 6–8 Ma ago. Molnar et al. (1993) argued that the maximum elevation of the Tibetan Plateau was attained only after lower lithosphere was convectively destabilized and removed resulting in 1000–2500 m of uplift in a few million years. The resulting increase of potential energy of the plateau would provide the large force required to cause folding and faulting of Indo-Australian lithosphere at ca. 8 Ma ago.

MORE TIMING

A second approach for estimating the timing of deformation and motion between the Indian and Capricorn plates comes from plate reconstructions. Gordon et al. (1998) and DeMets et al. (2005) estimated the motion between the Indian and Capricorn plates by separately estimating the motion of each plate relative to the Somalian plate, then differencing these estimates. They showed that motion across this diffuse oceanic plate boundary began more than 10 Ma earlier than inferred from the seismic stratigraphy and drilling. They hypothesized that the earliest interval of measurable motion,

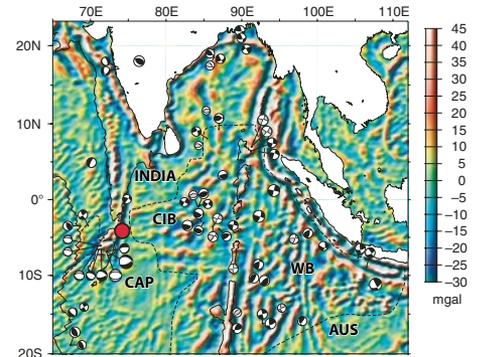


Figure 1. Tectonic map of the equatorial Indian Ocean showing band-pass filtered gravity and focal mechanisms for earthquakes with moments $> 3 \times 10^{16}$ N-m (black-filled solutions are Harvard centroid-moment-tensor solutions; gray-filled solutions are from Bergman et al. [1984] and Levchenko [1989]). Solid black curve near left edge of figure shows trace of the Central Indian Ridge and transform system. Dashed curves show the edges of diffuse oceanic plate boundaries. Filled-red circle is the pole of rotation between the Indian (INDIA) and Capricorn (CAP) plates. Divergence is accommodated west of the pole of rotation and convergence is accommodated east of the pole of rotation. The filtered gravity reveals east-west-striking undulations in the Central Indian Basin (CIB) and northeast-southwest-striking undulations (superposed on north-south fracture zones and volcanic topography) in the Wharton Basin (WB), thought to be lithospheric folds. The Australian plate (AUS) begins in the lower right part of the figure. After Royer and Gordon (1997).

which began more than 18 Ma ago, may coincide with inferred rapid denudation of the Tibetan Plateau from 21 Ma to 15–17 Ma ago (Harrison et al., 1992), but an even earlier age for the onset of motion could not be excluded. By tracking India-Capricorn motion at 20 distinct times steps over the past 20 Ma, DeMets et al. (2005) were able to show that the present episode of faster motion across the central Indian basin began at ca. 8 Ma ago. Their pole of rotation for 20–8 Ma ago, near 5°N, 85°E, predicts (but not at the 95% confidence level) that a larger portion of the pre-8 Ma boundary was extensional and less of it was contractional than is the case today.

Now, Krishna et al. (2009; p. 227 in this issue) have largely resolved this major discrepancy in

timing between the plate reconstructions and the seismic stratigraphy. To do so, they measured vertical offsets on three major unconformities and a continuous reflector above basement across 293 dip-slip faults on seismic reflection profiles in the diffuse plate boundary. In some cases, they also measured vertical offsets for other reflectors. The data are back-stripped to determine how vertical displacement accumulated with time. While finding that contractional strain accelerated at 7.5–8.0 Ma ago, they show that 12% of the thrust fault population had already been active before then, with contractional deformation initiating ca. 14–15 Ma ago. Moreover, they found that some faults incurred an earlier episode of normal faulting near or before 20 Ma ago.

Although the lithospheric folding started at 7.5–8 Ma ago, and 86% of the total strain occurred since 7.5–8 Ma ago, deformation at a slower rate began much earlier, in broad agreement with the conclusions reached from plate reconstructions.

TIBET TIMING

Thus, the plate reconstructions and deformation studies from seismic reflection profiles are now largely reconciled. But what about the timing of surface uplift in the Tibetan Plateau? Much work has also tested and challenged the premise that the Tibetan Plateau reached maximum elevation at ca. 8 Ma ago. For example, from an analysis of well-preserved fossil leaf assemblages from the Namling basin, southern Tibet, Spicer et al. (2003) concluded that the elevation of the southern Tibetan Plateau probably has remained unchanged for the past 15 Ma, and Rowley and Currie (2006) used stable isotope paleo-altimetry to show that central Tibet has been at an elevation similar to its modern elevation since ca. 35 Ma ago. Thus, within uncertainties (roughly ± 1 km), it appears that the Tibetan Plateau was at its present elevation long before 8 Ma ago, clearly contradicting the specific hypothesis of large (>1000 m) and rapid uplift at ca. 8 Ma ago proposed by Molnar et al. (1993).

Thus, the current estimates of the timing of both the initiation of India-Capricorn deformation and the attainment of elevations like those of today in Tibet are much greater than the 8 Ma ago assumed by Molnar et al. (1993). Because not one but both age estimates have become significantly greater, however, they remain consistent with the broader hypothesis that the outward push of an elevated Tibetan Plateau is what drives the deformation in the equatorial Indian Ocean. By 20 Ma ago, and perhaps much earlier, the force per unit length was apparently large enough to cause the lithosphere of the equatorial Indian Ocean to fail.

But ca. 8 Ma ago still marks an important change in kinematics and dynamics. The

angular rate of India-Capricorn motion roughly tripled (DeMets et al., 2005), contractional strain accelerated, and lithospheric folding initiated at 7.5–8.0 Ma ago (Krishna et al., 2009). Despite the important new information from paleo-altimetry, the deformation history of the equatorial Indian Ocean is telling us that the force from the Tibetan Plateau increased significantly at ca. 8 Ma ago. Thus, a sudden increase in plateau height at ca. 8 Ma ago seems required by the observed deformation in the equatorial Indian Ocean, but the paleo-altimetry results limit this to less than ~ 1000 m, instead of the more drastic increase of 1000–2500 m proposed by Molnar et al. (1993).

Therefore, it seems likely that the Tibetan Plateau, part of the planet's most important diffuse continental plate boundary, is intimately linked to the kinematics and dynamics of the equatorial Indian Ocean, the location of the planet's most important diffuse oceanic plate boundary.

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