Ridge torques and continental collision in the Indian-Australian plate

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ABSTRACT

The excess gravitational potential energy of a collisional orogen that may be supported by focusing distributed ridge torques in a plate depends on the ratio l of the effective lengths of ridge systems and collisional fronts. In the Indian-Australian plate, the net torque due to the asymmetric distribution of mid-ocean ridges and young oceanic lithosphere along the southern boundary is ~8.5 × 10^{25} N m and is capable of supporting an excess potential energy of the Himalayan collision zone of up to 7.5 × 10^{12} J/m^2. The concept that collision in the Indian-Australian plate may be sustained by ridge torques suggests that collisional driving stresses may be sensitive to l. In the Indian-Australian plate, l changed significantly during progressive collision from ~55 to 45 Ma, during amalgamation of the Indian and Australian plates at ~45 Ma, and during the development of the New Guinea orogen through the late Oligiocene and Miocene. Such changes in l may help explain the termination of spreading between India and Australia following the onset of the Himalayan collision and the early Miocene normal faulting in the high Himalaya.

INTRODUCTION

The continental collision between India and Asia over the past 50–55 m.y. provides one of the most dramatic manifestations of tectonism of modern Earth (Molnar and Tapponier, 1975). Although the kinematics of the collision have been elucidated in great detail, the magnitude and origin of the stresses that drive the collision are only poorly understood. Because some of the work done in the collision process may be stored as gravitational potential energy in the resulting orogens, a lower bound on the forces driving collision may be deduced from estimates of the excess potential of the Himalayan collision (Molnar and Lyon-Caen, 1988). For example, the excess gravitational potential energy, U_l, of the Tibetan Plateau has been estimated to be ~5–8 × 10^{12} J/m^2 (Molnar and Lyon-Caen, 1988; England and Houseman, 1989).

An apparent gravitational potential energy balance between mid-ocean ridges and continents with a surface elevation of ~1 km (England and Houseman, 1989) has led some authors to suggest that the forces generated as a consequence of the density changes accompanying the aging of the ocean lithosphere (commonly referred to as "ridge push") cannot drive a collision such as the Himalayan (England and Molnar, 1991). This logic would seem to justify an important role for other forces, such as those acting on subducting slabs, in sustaining collision between the Indian-Australian and Asian plates (Patriat and Achache, 1984; Cloetingh and Wortel, 1986; England and Molnar, 1991). However, such logic applies only to plates where the effective lengths of the mid-ocean ridges and the continental orogen are equivalent; in the Indian-Australian plate, the length of the mid-ocean ridge system along the southern boundary of the plate is many times greater than the Himalayan front (see Table 1). Furthermore, the role of subducted lithosphere in the deformation of surface plates may be limited in the Indian-Australian and other plates. For example, the large slab pull arising from the thermal and compositional density defects in subducting slabs appears to be nearly balanced by local resistance to slab penetration (Forsyth and Uyeda, 1975; Richardson et al., 1979; Richardson, 1992). Furthermore, a subduction-driven Indian-Australian plate regime in which slab pull is not locally balanced should lead to large, northeast-directed tensional stresses in the central Indian ocean. Although the majority of recorded mechanisms in this region are strike slip, several reverse earthquake mechanisms seem to preclude significant slab pull affecting this part of the Indian-Australian plate (Fig. 1).

An important insight into the role of collision at the plate scale is provided by the observation that the Indian plate velocity slowed appreciably following initial collision with the southern Asian margin at about 55–50 Ma (anomalies 24–22) through to 45 Ma (anomaly 20), when the full Himalayan collisional front was established (Patriat and Achache, 1984). This deceleration implies that the collisional forces are comparable to those that drive plate motion (Molnar and Tapponnier, 1975). The aim of this paper is to evaluate the extent to which focusing of ridge torques in the Indian-Australian plate could drive the Himalayan collision. At the outset we note that our arguments are not inherently new in as much as they have been briefly alluded to by Bird (1976) and England (1983), and possibly others, who have suggested that the ridge systems of the Indian-Australian plate are more than capable of driving the Himalayan collision. However, there continues to be widespread confusion concerning this problem; given its importance for the basic mechanism of plate tectonics, we believe that a reassessment of the argument is timely. Moreover, previous workers have not attempted to evaluate the effects of the complicated geometrical features of the Indian-Australian plate.

RIDGE TORQUES IN THE INDIAN-AUSTRALIAN PLATE

The conditon of zero acceleration in a plate constrained to move on the surface of Earth requires that the net sum of the torques associated with all forces acting on the plate is zero (Forsyth and Uyeda, 1975). In the Indian-Australian plate, the long length of ridge systems, combined with the asymmetric distribution of mid-ocean ridges around the plate margin, gives rise to a large net ridge torque, T_o, which potentially drives the plate motion. Because the potential energy of ocean lithosphere correlates with age and therefore with bathymetry (e.g., Coblentz et al., 1994), T_o is readily obtained by integrating over the surface, A_o, of the plate (Richardson, 1992):

$$T_o = \int_{A_o} \nabla U_l \times r \, d \, A_o, \tag{1}$$

where r is the radius position vector. For the Indian-Australian plate, we estimate T_o to be ~8.5 × 10^{25} N m about a pole at lat 30.3°N, long 34.5°E. The close correspond-

TABLE 1. BOUNDARY LENGTHS IN THE INDIAN-AUSTRALIAN PLATE

	0 Ma	5.3 Ma	23.7 Ma	36.6 Ma	57.8 Ma	
					India	Australia
Total ridge length (km)*	10860	10820	10770	10200	3810	8170
Effective ridge length (km)†	8360	8330	8310	7860	3700	4300
Himalayan orogen (km)§	2300					
Papua New Guinea (km)	1200					

* From plate reconstructions of Royer et al. (1992).
† Defined as the component parallel to the Himalayan orogen.
§ We treat the effective collisional boundary as that section of the convergent zone bounded by the two prominent syntaxes, extending from the vicinity of Mardan (long 72°05′E, lat 34°14′N) to Dibrugarh (long 94°56′E, lat 27°29′N).

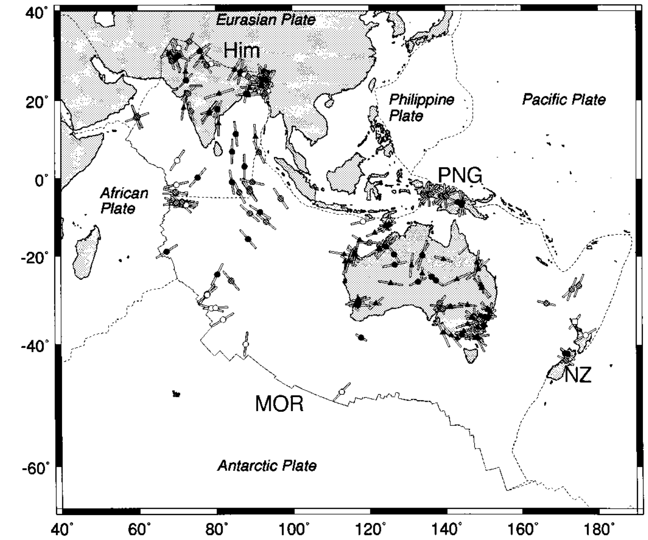

Figure 1. Indian-Australian plate with boundaries as defined by Minster and Jordan (1978) and Chase (1978). Him—Himalaya, PNG—Papua New Guinea, NZ—New Zealand, and MOR—Mid-ocean ridge. Stress indicator data for Indian and Australian plates are from World Stress Map database (Zoback, 1992). Circles represent focal mechanisms; squares represent geologic indicators; triangles represent well-hole data. Solid, open, and patterned stress indicator symbols represent compressional, extensional, and strike-slip deformational style, respectively. Open bars designate orientation of maximum horizontal compressive stress (S_{Hmax}). Lengths of vectors representing S_{Hmax} have been weighted by indicator quality (A–C) after Zoback (1992).

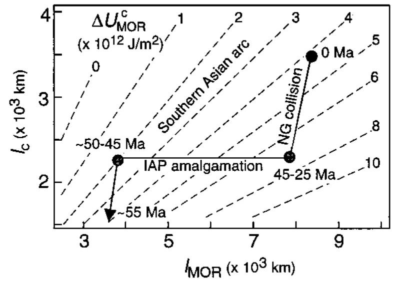

Figure 2. Illustration of dependence of ΔU^{c}_{MOR} on effective lengths of collisional fronts l_c and ridge systems l_{MOR}, assuming that ΔU^{MOR}_{oo} = 2.9 × 10^{12} J/m^2. Changes in effective lengths of ridge and collisional boundaries in Indian-Australian plate since commencement of collision at ~55 Ma (Table 1) are inferred from data of Royer et al. (1992). IAP—Indian-Australian plate; NG—New Guinea.

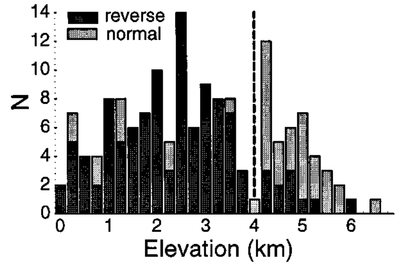

Figure 3. Histogram of stress indicators in Tibet-Himalaya region, plotted as function of elevation, showing that break between reverse and normal stress regimes occurs at ~4 km elevation. Data are from World Stress Map database (Zoback, 1992).

ence between the torque pole and the velocity pole (lat 19.2°N, long 35.6°E) supports the notion that the ridge torque helps drive plate motion and therefore may play an important role in maintaining the collision between India and Asia.

To examine the extent to which the ridge torque may drive collision in the Indian-Australian plate, it is useful to consider a limiting case in which the only torques acting on the plate are T_o and a corresponding resisting torque produced by collisional boundaries, T_c. For this purpose it is useful to determine the parameters of T_o in terms of an effective ridge length parameter, l_{MOR}, and T_c in terms of an effective collision length parameter, l_c (see Appendix). In terms of l_{MOR} and l_c, plate torque balance requires:

$$\Delta U^{MOR}_{oo} l_{MOR} = \Delta U^{c}_{oo} l_c, \qquad (2)$$

where ΔU^{MOR}_{oo} and ΔU^{c}_{oo} represent the difference between the potential energies of the mid-ocean ridge and old ocean (> ~80 Ma) (~2.9 × 10^{12} J/m^2), and collisional orogen and old ocean, respectively. Equation 2 can be readily reformulated in terms of the difference between the potential energy of a collisional orogen and a mid-ocean ridge:

$$\Delta U^{c}_{MOR} = 2.9 \times 10^{12}(l' - 1), \qquad (3)$$

where l' is the ratio of effective ridge lengths to collison lengths ($l' = l_{MOR}/l_c$).

Equation 3 provides a very simple basis for evaluating the possible focusing of ridge torques during collision, although application to real plates is compounded by the complex boundary geometries that characterize such plates. For example, in the Indian-Australian plate the ridge torque and the Himalayan collisional torque are clearly not antiparallel, as would be required if they were the only torques acting on the plate. Nevertheless, approximate estimates may be obtained by using estimates of the effective ridge and collision lengths in natural plates derived by various simplifying assumptions (Table 1). For example, assuming that the maximum component of the Indian-Australian plate ridge torque is focused on the Himalayan collision gives an estimate for l' of 3.6 and for ΔU^{c}_{MOR} of 7.5 × 10^{12} J/m^2 (Fig. 2). The inclusion of the New Guinea collision (with an estimated length of 1200 km) in the torque balance reduces the estimated value of l' for the Indian-Australian plate to ~2.4, giving ΔU^{c}_{MOR} of 4 × 10^{12} J/m^2.

As discussed in the introduction, an important constraint on the magnitude of the resistance imposed along the Himalayan collision is given by the excess potential energy of that collision. Using assumed lithospheric density models, Molnar and Lyon-Caen (1988) and England and Molnar (1991) estimated the potential energy of the Tibetan plateau (at ~5 km elevation) to be ~5–8 × 10^{12} J/m^2 greater than that of the mid-ocean ridges. However, because the Tibetan plateau is currently in an extensional regime, it cannot be supported completely by Indian-Australian plate driving mechanisms, and we suggest that the excess potential energy appropriate to the transition from dominantly reverse to normal faulting (Fig. 3) at ~4 km elevation (England and Molnar, 1991) provides the best measure of the support currently provided by Indian-Australian plate driving mechanisms. The excess potential energy of the orogen at 4 km of elevation is estimated at ΔU^{c}_{MOR} (Himalaya) ~4–6 × 10^{12} J/m^2, which is comparable with the previously cited estimates of the excess potential energy that may be supported by focusing distributed ridge torques.

The simple approach to the torque balance presented above, which predicts mean stress differences ($\sigma_1 - \sigma_3$) in the Himalaya of 45–70 MPa, is supported by finite element computations designed to accommodate the effects of complex boundary geometries in the Indian-Australian plate (Fig. 4). We have used a finite element grid consisting of 1374 nodes in a network of 2527 constant-strain triangular elements. The spatial resolution of the grid is ~2°, and therefore the sensitivity of the modeled stresses is limited to features with wavelengths of a few hundred kilometres. Stress magnitudes are calculated for a lithosphere of constant thickness, assumed to be 100 km. All elements were assigned a Young's modulus of 7 × 10^{10} N/m^2 and a Poisson's ratio of 0.25. The excess potential energy of the ridges is distributed as a pressure gradient over the young oceanic lithosphere (Richardson, 1992). Mechanical equilibrium is achieved by fixing the Himalayan, Papua New Guinea, and New Zealand boundary segments, which is equivalent to assuming that all resistance is focused along these bound-

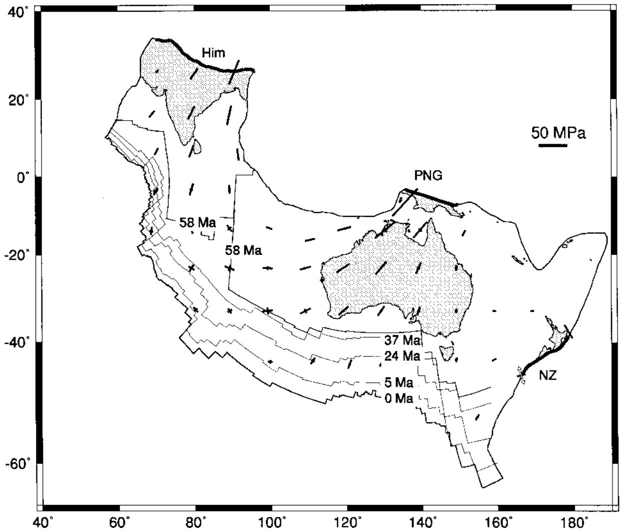

Figure 4. Principal stresses predicted by finite element analysis of Indian-Australian plate. Solid bars indicate deviatoric compression, open arrows indicate deviatoric tension. Ridge locations are shown for Pliocene (5.3 Ma), Miocene (23.7 Ma), Oligocene (36.6 Ma), and Eocene (57.8 Ma) (from Royer et al., 1992). PNG is Papua New Guinea; N2 is New Zealand; Him is Himalaya.

aries. We note that these boundary conditions obviously provide a simplistic analysis, which cannot account for all features in the Indian-Australian plate stress field. We are encouraged, however, that such a simple analysis reproduces (Fig. 4) many of the main long-wavelength features of the Indian-Australian plate in-situ stress orientations (Fig. 1), without predicting abnormally high stress magnitudes (cf. Cloetingh and Wortel, 1986). In particular, the predicted stress field in the central Indian Ocean is consistent with the observed stress regime bordering strike-slip and reverse regimes. The predicted tectonic stress field is compressional throughout the plate; the maximum horizontal compressive stress is oriented north-south in India and northeast-southwest in western Australia. Focusing along the fixed boundary segments results in compressional stress differences averaging 45 MPa along the Himalayan collision zone. We note that the calculations show a strong gradient in the magnitude of the differential stress along the length of the Himalayan front, increasing from ~15 MPa near the western syntaxis to ~90 MPa in the eastern syntaxis. In contrast, there is negligible variation in the magnitude of tectonic stresses predicted along the New Guinea collision zone, where the average $(\sigma_1 - \sigma_3)$ is 90 MPa, reflecting the fact that this collision zone is nearly orthogonal to the net ridge torque on the Indian-Australian plate.

DISCUSSION

The calculations presented here support the notion that focusing of ridge torques could drive the Himalayan collision and thus testify to the fallacy of the argument that because the potential energy stored in continental collisional orogens such as the Himalaya exceeds that of the mid-ocean ridge on a per unit length basis, such orogens cannot be supported by ridge torques. Our calculations do not preclude a role for other forces, such as those associated with subducting slabs, in driving the collision, but they do remove one of the principal grounds for appealing to such processes as a fundamental requirement for the development of collisional orogens. As discussed above, the role of slab pull may be quite small because of local torque balance, as evidenced by the absence of large, northeast-directed, tensional stresses in the central Indian Ocean.

Our calculations support the hypothesis of a subtle balance between the plate-scale ridge torques in the Indian-Australian plate and the potential energy of the Himalayan orogen. The notion that the interior part of the Himalayan orogen, in the Tibetan plateau, represents a pressure gauge recording subtle variations in force balance in its incremental strain history is by no means new (Molnar and Tapponnier, 1975; Molnar and Lyon-Caen, 1988), and is implicit in the notion that dynamically the collision balances ridge torques. This hypothesis suggests that the magnitude of the potential energy of the orogen supported by distributed ridge torques is very sensitive to l'. Under general circumstances, l' would be expected to change as convergence proceeds, possibly catastrophically. Moreover, this sensitivity to l' suggests that significant insights into the dynamic evolution of collisional belts may be obtained by reconstructing the time evolution of l_{MOR} and l_c (Fig. 2).

The complex Paleocene-Eocene motion in the Indian plate between anomaly 24, when collision began, and anomaly 20, when final amalgamation with the Australian plate occurred, has been related to the developing Himalayan collision (Molnar and Tapponier, 1975), the overall deceleration consistent with collisional forces being of the same order as plate driving forces. Patriat and Achache (1984) argued that "termination of spreading at this ridge (between India and Australia) seems to be a consequence rather than a cause of the plate reorganization" and concluded that the chronology of events in the Indian Ocean was inconsistent with ridge torques being a dominant driving force during the collisional episode. Here we reassess this plate reorganization using estimates of total and effective ridge lengths of the Indian-Australian plate and the Indian and Australian plates prior to and following amalgamation (Table 1). The location of the ridge axis in the Pliocene (5.3 Ma), Miocene (23.7 Ma), Oligocene (36.6 Ma), and Eocene (57.8 Ma) are shown in Figure 4, and estimates of the ridge lengths are given in Table 1.

Collision first occurred along the northwestern end of the Himalaya between India and the Ladakh arc during anomaly 24; continental collision between the northern Indian passive margin and southern Asian margin possibly did not occur until anomaly 22. The collisional front was established by about anomaly 20 (Patriat and Achache, 1984). In terms of l', this evolution represents a decrease from an initially very high value to ~1.6 by anomaly 20 (Fig. 2). For $l' = 1.6$, ridge torques are able to support a maximum $\Delta U^{c}_{\mathrm{MOR}}$ of only $\sim 2 \times 10^{12}$ J/m^2 (Fig. 2). Following amalgamation of the Indian-Australian plate, the effective ridge length was comparable to the modern-day length, l' of ~3.5 supporting $\Delta U^{c}_{\mathrm{MOR}}$ of up to $\sim 7 \times 10^{12}$ J/m^2. As discussed by Molnar and Lyon-Caen (1988), collision may normally be expected to involve the building of a narrow orogenic belt that widens progressively to develop a plateau, the excess potential energy of the plateau balancing the driving forces. However, the development of the Himalayan orogen is likely to be somewhat more complex because of the existence of a subduction-related Cordilleran-style margin along the southern Asian continent (England and Searle, 1986; Rex et al., 1988) prior to collision. Subduction commonly results in the generation of very significant potential energy gradients in the overriding plate which are presumably supported by tractions at the subduction interface. For example, geoid anomalies of about 24–27 m across the Andean Altiplano suggest an excess potential energy of $\sim 4–6 \times 10^{12}$ J/m^2 (Froidevaux and Isacks, 1984). England and Searle (1986) have shown how the existence of such potential energy contrasts at the southern Asian margin could displace the locus of collisional deformation to the north, consistent with the absence of significant Tertiary deformation in the Lhasa block. With collision and the termination of subduction, support for any existing excess potential energy contrasts along the southern Asian margin must have been transmitted to the converging plate. If the existing excess potential energy of the southern Asian margin was greater than about 2×10^{12} J/m^2, the net ridge torque in the Indian plate could not have supported the full Himalayan collision front. One obvious solution to this problem was the amalgamation of the Indian-Australian plate, which, with the consequent establishment of a very long ridge segment, allowed ongoing collision driven by the newly established distributed ridge torques of the Indian-Australian plate (Fig. 2). Thus, contrary to Patriat and Achache (1984), a "ridge-driven" plate regime seems to demand that the continuation of collision between India and Asia after anomaly 20 was contingent upon amalgamation of the Indian and Australian plates.

Collision along the New Guinea segment of the Indian-Australian plate began in the late Oligocene (Pigram and Symonds, 1991), and the length of the collisional segment increased through the Miocene as Australia impinged on the Banda arc. The consequent reduction in the effective value of l' at the plate scale may be expected to have lowered significantly the driving stresses along other collisional fronts such as the Himalaya, possibly to the level where the excess potential energy of the highest parts of the Himalayan orogen initiated extension. Extension in the Tibetan plateau has been proceeding at least since late Miocene time where the onset of extension has been correlated with the uplift of the plateau, possibly related to convective removal of the mantle lithosphere (England and Houseman, 1989; England and Molnar, 1991). In this scenario extension represents the mechanical response to an increase in U_l in excess of that which can be supported by prevailing driving forces. There has been less consensus on the significance of an older (early Miocene) set of shallow, north-dipping normal faults that extend for great lengths along the high Himalaya (Burg et al., 1984; Burchfiel et al., 1992) into the Karakoram (Rex et al., 1988). The analysis presented here suggests the possibility that this older set of faults represents the response to a catastrophic reduction in the driving stresses in the Himalaya associated with the development of the New Guinea orogen, and lends intrigue to the hypothesis of a ridge-driven plate regime in the Indian-Australian plate.

APPENDIX

As discussed in the text, the ridge torque T_o may be obtained by integrating U_l over the oceanic parts of the plates; however, considerable simplification is provided by approximating T_o in terms of an effective ridge length parameter l_{MOR}. To do so, we note that the effective torque acting on the plate due to a ridge segment of unit length is $\sim\Delta U_{oo}^{MOR}$ n, where n is the unit ridge-normal vector in the direction of plate aging and ΔU_{oo}^{MOR} is the potential energy difference between the mid-ocean ridge and old oceanic lithosphere. The ridge torque can then be approximated by integrating over the total length of the ridge segments R;

$$T_o = \int_R (\Delta U_{oo}^{MOR}\, n) \times r\, dr,$$

and allows us to define the effective ridge length

$$l_{MOR} = \frac{|T_o|}{|(\Delta U_{oo}^{MOR}\, n) \times r|}.$$

The torque due to potential energy variations in the continental collisions T_c can similarly be used to define an effective collisional length parameter

$$l_c = \frac{|T_o|}{|(\Delta U_{oo}^{c}\, n) \times r|},$$

where ΔU_{oo}^{c} is the characteristic potential energy difference between the continental lithosphere along the collisional plate boundary and old ocean lithosphere.

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