Chapter 11

The driving mechanisms reviewed

We have seen that significant forces are associated with the changes in potential energy, accompanying the generation and ageing ocean lithosphere and its subduction; forces which we refer to as *ridge push* (about 2-3 x 10^{12} N m^{-1} as seen by old ocean lithosphere) and *slab pull* (up to the order of 10^{13} N m^{-1}). Similarly, potential energy variations associated with continental topography are capable of generating large buoyancy forces. In addition, the passage of the lithosphere over the deeper, hotter convective mantle, or, viceversa, the traction exerted by the convective flow on the base of the lithosphere, may act to either resist or drive plate motion (Fig 11.1). An important constraint on the way these tectonic forces interact is provided by the observation that individual plates are not accelerating. This requires that a basic force balance or, more strictly, a torque balance operates on individual plates. In the following discusion we consider the implications of this reuirement for torque balance for the driving mechanisms a number of the Earth's plates.

11.1 Torque balance and plate velocity.

A force acting on a lithospheric plate produces a torque, **T** whose magnitude is given by the cross product of the force **F** and the radius of the Earth (defined by the radius vector,**T**) :

$$\mathbf{T} = \mathbf{F} \, \mathrm{x} \, \mathbf{r}$$

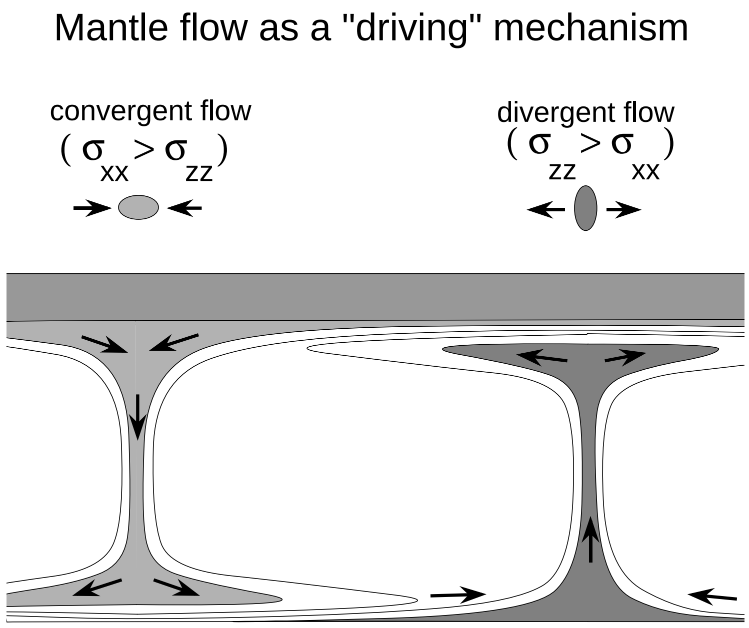

Figure 11.1: Mantle flow as a driving mechanism.

with a torque pole given by the *left-hand rule.*

The notion that the plates are not appreciably accelerating implies a torque balance, which must reflect the interaction between forces which drive plate motion and those that resist plate motion. It seems reasonable (to me at least) to assume that the torque pole of the force and/or combintaion of forces driving plate motion is correlated with the velocity pole, and thus we should be able to identify the driving forces from the resistive forces, by comparison of torque poles and velocity poles.

There is substantial variation in the absolute velocity of the Earth's major plates which correlates to some degree with the gravitational torques acting on the plate (see reprint Coblentz et al. *On the Potential energy of the Earth's lithosphere*)

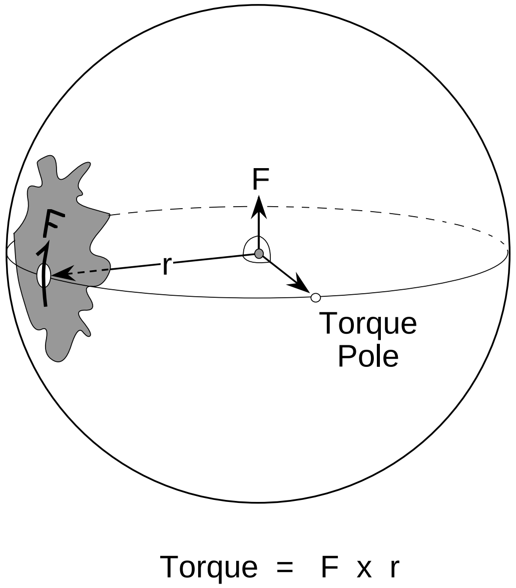

Figure 11.2: Torque balance.

11.2 The African plate

The African and Antarctic plates are similar in as much as they are both large, slowly moving plates, incorporating significant continental areas bounded amost entirely by passive margins and oceanic ridge systems with only minor lengths of convergent margin boundaries. Moreover, both are characterised by relative slow absolute velocities and by active continental tectonics dominated by rifting (e.g., the African rift system in Africa and the Ross Sea- Trans-Antarctic Mountain rift system).

Traditionally, the rifting that has occurred in the continental regions of both plates has been seen as the consequence of a process actively involving the sub-lithospheric mantle, such as the impingement of a plume on the base of the lithsophere (such as illustrated in Fig. 11.1). It is estimated that the imingement of a plume at the base of the lithdophere can jack the lithsophere upo by as much as 1-2 kms, with a corresponding increase in potential energy of up to 3 x 10^{12} N m^{-1}. While this is undoubtedly an important process in generating extensional stress regimes in continents, another possibility is simply related to the way in which potential energy is distributed across the plate and how this potential energy distribution evolves in time as the oceans spread outward around the continent. To understand this it is useful idealise the African Plate as a completely circular plate which has grown uniformily with time (Fig.11.3), and imagine how the potential energy of the plate evolves with time. What is growing with time is largely the old ocean lithosphere which represents a potential energy low within the plate. Consequently, the mean plate potential energy must decline with time, and the difference between the continental potential energy and the mean platte potential energy becomes progressively greater producing significant tension in the most elevated parts of the continent.

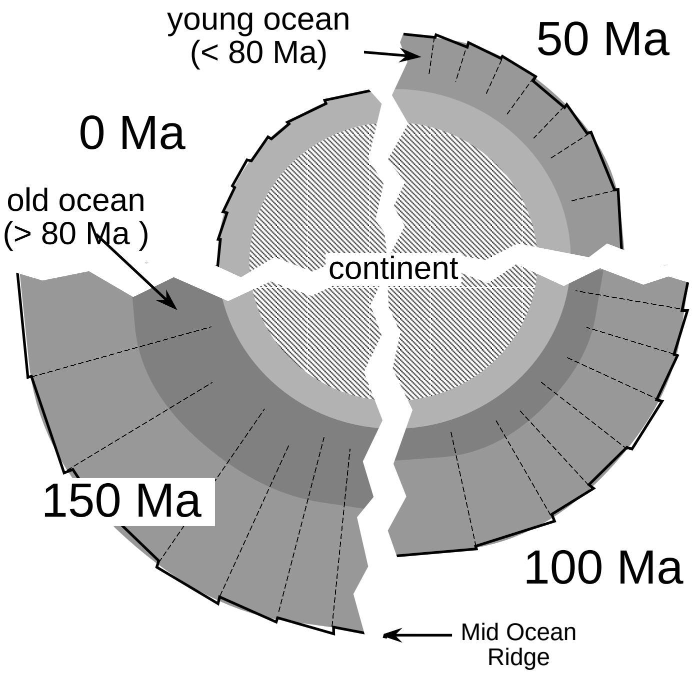

Figure 11.3: Circular plate analogy to the African and Antarctic Plates.

For those interested more details can be found in the reprints Sandiford & Coblentz :*Plate scale potential energy differences and* *the fragmentationof ageing plates*), and Coblentz & Sandiford, *Tectonic Stresses in the African Plate: Constraint on the Ambient Stress State.*

11.3 Torque balance in the Indo-Australian Plate

The Indo-Australian (IAP), North American and South American plates form a group of fast moving "continental" plates (Minister & Jordan, 1978). In the North American and South American continents the orientation of the maximum horizontal compression ($\mathrm{SH_{max}}$) is well defined and is clearly aligned with the absolute plate velocity (Richardson, 1992). In contrast, the intraplate stress field within the Australian continent is complex, and thus cannot easily be explained by any single tectonic process. Like North America and South American, but unlike the slower moving plates such as Europe and Africa, the stress field within the interior of the Australian continent is largely compressional. In the northern part of the plate $\mathrm{SH_{max}}$ is aligned N to NNE more or less orthogonal to the collisional boundary in New Guinea. Elsewhere, the orientation of SHmax forms a divergent fan resulting in E-W compression in western Australia, in south-eastern Australia and along the southern margin. While the stress field in the northern and western part of the continent have been relatively successful modelled in terms of plate-scale tectonic processes (Cloetingh & Wortel, 1985,1986; Richardson, 1987; Coblentz et al., 1993a), the sources of the E-W compression in SE Australia remains poorly understood.

In the North and South American plates, the uniform intraplate stress field orientation reflects, in part, the relatively homogeneous boundary configuration of the plates; both having relatively long mid-ocean ridge segments along their trailing (eastern) margins and long continental arc-related mountain tracts along the leading (western) margins. While the IAP is similarly configured with cooling ocean lithosphere dominating the entire southern boundary, the northern and eastern convergent boundaries are heterogeneous consisting variously of continent-continent collisions (Himalaya, New Guinea, New Zealand), continent-arc collisions (Banda Arc), and oceanic-trench segments (Java Trench, Tonga-Kermadec trench). Below we show that the compressive stress pattern in the central and western part of the Australian continent relates to focussing of stresses arising from the plate-scale distribution of gravitational potential energy along the Himalayan and New Guinea collision segments. We then show how similar notions applied to the eastern boundary naturally account for the enigmatic EW compression observed in SE Australia, and, if correct, considerably down-plays the role of subduction and basal traction in the IAP intraplate stress field.

At the outset it is necessary to emphasize that the main constraint we will use here to evaluate the origins of the Australian stress field are the orientations of the in situ stress field. There is now a considerable dataset on stress orientations for the IAP (Zoback,1992). In contrast, our knowledge of stress magnitudes is very poor, and remains the subject of some controversy. This is especially the case for the central Indian Ocean, which is unique in having active deformation of the oceanic lithosphere in the central Indian Ocean (refernces).

The sources of stress that act on plates include: (1) intraplate sources related to lateral variations in gravitational potential energy of the lithosphere (Coblentz et al., 1993b), (2) tractions transmitted across convergent plate margins and (3) tractions at the base of the plate related to its motion over the asthenosphere. The best understood of these are the intraplate variations in potential energy in the ocean lithosphere which give rise to "ridge push" of about 2-3 x 10^{12} N m^{-1} of young ocean lithosphere on old (¿ 80 Ma) ocean lithosphere (note that variations in lithopsheric potential energy can be directly related to geoid anomalies which for ocean ridges are of the order of 10-15 m, Sandwell & Schubert, 1980). Other intraplate sources are associated with continental margins where the difference in potential energy is of the order of 1-2 x 10^{12} N m^{-1} (with a corresponding geoid anomaly of about 6 m, Haxby & Turcotte, 1978; Coblentz & Richardson, 1992; Coblentz et al., 1993b) and with areas of high topography developed at continental collisional margins (see discussion below). In comparison with these intraplate stress sources, the magnitudes of stresses imposed at convergent margins and the tractions at the base of the plate are poorly constrained, and estimates very by orders of magnitudes (c.f., Cloetingh & Wortel, 1985 & 1986; and Richardson, 1987). While the negative buoyancy of subducting lithosphere is relatively easy to quantify (of the order of a few times 10^{13} N m^{-1} for a fully developed slab), and potentially provides a large "net" tensional force to the trailing plate, the extent to which the stresses arising from the density defect are dissipated in the subduction zone is not known. More controversial are the "trench suction" forces transmitted to the over-riding plate at subduction zones which may apparently be either compressional or tensional. Continent-continent and continent-arc collisions are likely to impose considerable resistance to plate motion because of the buoyancy of continental lithosphere and hence are likely to be a source of intraplate compression. Some idea of the magnitude of the forces associated with collisional processes can be determined by the change of the potential energy associated with the construction of convergent orogens. Precise quantification of these potential energy changes are difficult to establish because of our inadequate knowledge of the deep lithospheric density structure, and because we cannot accurately measure geoid anomalies on the continents. However, the crustal contribution to the excess potential energy of regions of high elevations is proportional to the square of the crustal thickening (e.g., England & McKenzie, 1982), and for the high Himalaya, where crust is approximately double the normal continental thickness may be as much as 5 - 10 x 10^{12} N m^{-1} (Zhou & Sandiford, 1992).

Because we have much more confidence in the magnitude of the intraplate sources of stress, than with forces associated with plate boundaries it is useful to model the effect of intraplate sources of stress without applying overly stringent boundary conditions (our modelling strategy is outlined in Appendix 1). We note that the lateral variations in the lithospheric potential energy provides substantial torques in a number of plates (e.g. Richardson, 1992, Coblentz et al., 1993). For plates with the largest gravitational torques (the Pacific, Indo-Australian and South American), there is good correlation between the gravitational torque poles and velocity poles (Coblentz et al., 1993), suggesting gravitational torques may be an important driving mechanism for plate motion. In the IAP the potential energy distribution produces a torque of 6.43 x 10^{25} N m about a pole at 27_o N, 62.4_o E which closely matches the velocity pole xx_o N, xx_o E (the angular misfit is 14_o). This torque is mostly reflects potential energy distributions of the ocean ridge systems along the southern and western margin of the plate (which contribute 8.3 x 10^{25} N m-1 about a pole at 40.7_oN, 31.7_oE, but also includes contributions from the continental masses.

The assumption that the lithospheric plates are not accelerating (Solomon, 197x; Richardson et al., 1979) and thus are in mechanical equilibrium required balance of the gravitational potential energy torque by some other forces. The close correspondence between gravitational potential energy torque poles and the plate velocity pole requires that the net some of the opposing forces act against in a sense that is resistive to the current plate motion. Such resistance may be achieved either by drag at the base of the plate or by resistance along the convergent margins, and in the following sections we describe the stress fields for each of these scenarios. Figure 2 shows that the stress field produced all resistance provided by basal shear bears little resemblance to the observed stress field. Thus, we consider it is likely that at least some of the torque balance is achieved by resistance imposed along the northern margin and in Figure 3 we show the the stress fields predicted by applying force balance by fixing the whole of the northern boundary and by fixing only those segments involving collision of continental lithosphere of the IAP, that is, Himalaya, New Guinea and New Zealand

The match between the observed and predicted stress fields is far better for Figure 3b than for Figure 3a, especially for the western Australia, suggesting that much of the compressional stress within the IAP is the result of focusing the potential energy torque (mostly arising form ridge push) along collisional boundary segments. The predicted occurrence of EW compression in SE Australia in Figure 3b is of particular importance in that it is in accords with the evidence of a range of in-situ stress indicators (e.g., Zoback, 1992) the origin of which hitherto has been enigmatic. This predicted compression arises from the collisional segment of the plate boundary in New Zealand.

An important aspect of the results indicated in Figure 3b is that the main features of the Australian continental stress field can be reproduced by the interaction of two governing processes, namely gravitational potential energy torques (mainly due to "ridge push") and collisional resistance. Figure 3b clearly shows that the main complexity in the stress field reflects the heterogeneous disposition of the collisional segments along the northern and eastern convergent boundaries of the IAP. If this interpretation of the intraplate stress field is correct it raises the important question of the role of subduction at convergent boundaries in the intraplate stress field, the implication being that subduction processes provide, at best, a second-order control on the IAP stress field. We return to this question following a discussion of the predicted stress magnitudes.

The main conclusions that stem form the work presented here, which may have important global implications are:

- torques arising from plate-scale potential energy distributions, including ridge push, are significant first-order controls on the in situ stress field (Richardson, 1992), even in plates with complex stress fields such as the IAP.
- the orientation and magnitude of the stresses resulting from plate-scale potential energy distributions may be significantly modified by focussing effects along heterogeneous convergent boundaries. Indeed, in order to develop significant compression within continents it may be necessary to have some focussing.
- the effects of subduction and basal shear are not necessary to explain the gross features of the Australian stress field, and thus seem to be second-order features.

Finally, the analysis presented here suggests that the complexity in the Australian stress field, in comparison with other continents such as North America and South America seems simply to reflect the heterogeneous convergent boundary conditions operating on the northern and eastern boundary. While the role of the northern boundary of the IAP has long been suspected, our new interpretation of the origin of the E–W compression in the SE Australia further emphasizes the importance of stress focussing at collisional boundaries.

Also See preprint Sandiford et al. *Focussing ridge torques during continental collision in the Indo-Australian plate*