A brief history of the Indo-Australian plate

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Abstract

1. Introduction

Understanding the way in which torque balance is achieved in the lithospheric plates continues to be major quest for geodynamicists. In particular, the nature of the response to major changes in torque balance (Figure 1) is a rich field that has been poorly investigated. The plates clearly provide the surface expression of the flow in the deeper mantle, although the coupling between deeper mantle processes and the lithospheric plates continue to remain enigmatic. Fundamental questions that remain controversial include the extent of dynamic topography generated by mantle flow (Gurnis et al., 1998; ), the extent to which pate boundary forces propagate stress across the surface plates, and the way that this torque balance is resolved in terms of the global pattern of stress. Insights into some of these questions can be obtained by providing a temporal framework for the evolution of plates over geological time (eg., Gurnis et al., 1998).
The Emperor Hawaii seamount bend at 43 Ma provides a potential record of significant plate acceleration at ca 43 ma (eg. Sutherland, in prep) that must relate to change sin torque balance on the Pacific plate.

Since the fragmentation of Gondwana, the configuration of the Australian plate has undergone several substantial dramatic changes in terms of the configuration of its plate boundaries including, most dramatically, the amalgamation of the Indian and Australian plates to form the present configuration of the Indo-Australian Plate (IAP; Figure 2). To the extent that the plate boundary configurations through much of this time can be recovered, the Australian plate provides an excellent opportunity to evaluate the response of the continental interior to changing boundary conditions. This paper provides a brief summary of the boundary configurations and continental response of the Australian plate over the late 150 Ma, focussing on the way in which the evolving plate scale torque balance has contributed to the intraplate stress field.
2. Torque balance in the modern Indo-Australian plate.

A critical concept used in this paper is the notion of torque balance, as used now for many years in understanding the dynamics of plate motion (e.g., Forsyth & Uyeda, 1975; Richardson, 1992; Coblentz et al., 1994). 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 assume that the torque pole of the force and/or combination 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.

Figure 2:
Australia forms part of the Indo-Australian plate (IAP) bounded along its southeastern margin by a mid-ocean ridge system, and along its northern and eastern boundaries by mixtures of collisional and subduction zones, providing a very heterogeneous plate boundary condition.
Figure x:

(a) Torque is given by the cross product of a surface force \( F \) and a balance applied. (b) The concept of torque balance as applied to a plate with heterogeneous plate boundaries providing the sources of stress that act on the plate. For zero acceleration, Newton's second law implies a torque balance at the plate scale.

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 (Forsyth & Uyeda, 1975; Richardson, 1992; Coblentz et al., 1994).

The Indo-Australian North American and South American plates form a group of relatively fast moving "continental" plates (Minster & Jordan, 1978). In the North American and South American continents the orientation of the maximum horizontal compression \( S_{H_{\text{max}}} \) 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 America, 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 \( S_{H_{\text{max}}} \) is aligned N to NNE more or less orthogonal to the collisional boundary in New Guinea. Elsewhere, the orientation of \( S_{H_{\text{max}}} \) forms a divergent fan (Figure 1) 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 (references).

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 lithospheric 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 et al., 1994) 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; 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 that 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} \text{ N m}^{-1} (Zhou & Sandiford, 1992).

![Figure x](image)

A measure of the excess potential energy of the Himalayan orogen supported by plate driving mechanisms is provided by the nature of seismicity which changes from dominantly reverse mechanisms at elevations below 4 kms to dominantly normal mechanisms at elevations above 4 kms (eg Sandiford et al., 1995).

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. 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., 1994). 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., 1994), 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} \text{ N m} about a pole at 27^\circ \text{ N}, 62.4^\circ \text{ E} which closely matches the velocity pole xx^\circ \text{ N}, xx^\circ \text{ E} (the angular misfit is 14^\circ). 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} \text{ N m}^{-1} about a pole at 40.7^\circ \text{ N}, 31.7^\circ \text{ E}, 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 x 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 x we show the stress fields predicted by applying force balance by fixing the whole of the northern boundary (Figure x) and by fixing only those segments involving collision of continental lithosphere of the IAP, that is, Himalaya, New Guinea and New Zealand (Figure x).

![Diagram of stress fields](image)

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:

1. 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.

2. 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.

3. 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.

3. Major events in the evolution of the Australian plate

The evolution of the Australian plate since separation form Antarctica can be reconstructed from the ages of ocean floor on the Indo-Australian plate (eg Mueller et al., 1998; Figure x)
Ocean floor ages from Mueller et al., 1998) digital datasets. Critical features include the extinct spreading centres in the north central Indian Ocean and the Tasman and Coral seas along Australia’s eastern seaboard.

Figure x
The Indian plate prior to collision
Formation of continental ribbons

The eastern margin of the Austrlian plate contains the best preserved examples of continental ribbons along the Lord Howe rise (Figure x). This ‘ribbons’ formed during opening of the Tasman Sea, and represent the fragmented remains of the extended continental margin of Australia during a period of extension.
Continental “ribbon” structure defined by the New Zealand and the Lord Howe rise.

Dynamic Topography
Figure x

Topography of the IAP warped onto the geoid, showing the gradient in geoid across which Australia is currently transiting

References


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