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Topography, boundary forces, and the Indo-Australian intraplate stress field

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Abstract. The relative contribution of topographic (e.g., ridge push, continental margins, and elevated continental crust) and plate boundary (e.g., subduction and collisional) forces to the intraplate stress field in the Indo–Australian plate (IAP) is evaluated through a finite element analysis. Two important aspects of the IAP intraplate stress field are highlighted in the present study: (1) if substantial focusing of the ridge push torque occurs along the collisional boundaries (i.e., Himalaya, New Guinea, and New Zealand), many of the first-order features of the observed stress field can be explained without appealing to either subduction or basal drag forces; and (2) it is possible to fit the observed $S_{H_{\max}}$ (maximum horizontal stress orientation) and stress regime information with a set of boundary conditions that results in low tectonic stress magnitudes (e.g., tens of megapascals, averaged over the thickness of the lithosphere) throughout the plate. This study therefore presents a plausible alternative to previous studies of the IAP intraplate stress field, which predicted very large tectonic stress magnitudes (hundreds of megapascals) in some parts of the plate. In addition, topographic forces due to continental margins and elevated continental material were found to play an important role in the predicted stress fields of continental India and Australia, and the inclusion of these forces in the modeling produced a significant improvement in the fit of the predicted intraplate stresses to the available observed stress information in these continental regions. A central focus of this study is the relative importance of the boundary conditions used to represent forces acting along the northern plate margin. We note that a wide range of boundary conditions can be configured to match the large portion of the observed intraplate stress field, and this nonuniqueness continues to make modeling the IAP stress field problematic. While our study is an important step forward in understanding the sources of the IAP intraplate stress field, a more complete understanding awaits a better understanding of the relative magnitude of the boundary forces acting along the northern plate margin.

1. Introduction

The Indo–Australian plate (IAP) is unique among the Earth's plates in its variety of first-order tectonic features, having a combination of active subduction zones, an extensive mid-ocean ridge system, significant areas of both continent-continent and continent-island arc collision, and regions of intraplate oceanic-lithosphere deformation. These features make the IAP an important place to study the relationship between tectonic forces (e.g., boundary and topographic forces) and the intraplate stress field. However, while deformation within the Indo-Australian plate is well documented, the origin of the tectonic stresses within the plate remains controversial. With the exception of the observed N–S compression in India and northern Australia, it has proved very difficult to correlate features of the observed intraplate stress field with specific tectonic forces. From a plate dynamics perspective, one of the unusual features of the Indo-Australian plate is the lack of a direct correlation between the ridge push force and the observed stress field, despite the extensive mid-ocean ridge system that dominates the entire southern plate boundary. Thus, in sharp contrast to most other plates, the IAP intraplate stress field is not readily explained by any single principal source, i.e., simple ridge push, slab pull, absolute plate motion, or collisional resistance force models [*Richardson*, 1992].

The magnitudes of the tectonic stresses within the IAP continues to be the subject of considerable con-

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troversy. Previous models of the intraplate stress field [e.g., *Cloetingh and Wortel* 1985, 1986] predicted very large intraplate stresses (of the order of hundreds of megapascals) throughout much of the IAP. The prediction of high intraplate stress magnitudes was justified by what was originally thought to be the existence of intraplate deformation in the central Indian Ocean (in the vicinity of the Ninety East Ridge roughly between 5°N and 10°S). This area has been the focus of numerous studies into the nature of the lithospheric deformation and its relationship to the intraplate stress field [e.g., *Stover*, 1966; *Curray and Moore*, 1971; *Sykes*, 1970; *Stein and Okal*, 1978; *Bergman and Solomon*, 1980, 1984, 1985; *Weissel et al.*, 1980; *Wiens and Stein*, 1983, 1984; *Bergman et al.*, 1984; *King and Stein*, 1984; *Patriat and Achache*, 1984; *Bratt et al.*, 1985; *McAdoo and Sandwell*, 1985; *Wiens et al.*, 1986; *Stein et al.*, 1989; *Neprochnov et al.*, 1988; *Bull*, 1990; *Bull and Scrutton*, 1990; *Pilipenko and Sivukha*, 1991; *Bull et al.*, 1992; *Chamot-Rooke et al.*, 1993; *Molnar et al.*, 1993; *DeMets et al.*, 1994; *Van Orman et al.*, 1995; *Buchanan et al.*, 1996]. While recent studies of the stress release associated with seismicity in this region support the notion of large intraplate stresses in this region [e.g., *Grovers et al.*, 1992], it is now generally accepted that the central Indian Ocean is the site of a wide diffuse plate boundary between distinct India and Australia plates rather than an example of interplate deformation. Given the nonuniqueness of the stress modeling problem (due in large part to our poor understanding of the magnitude of the plate boundary forces acting on the IAP), other previous modeling studies have shown that it is possible to explain the observed stress orientations with a combination of plausible tectonic forces, which generate intraplate stress magnitudes an order of magnitude less, i.e., tens of megapascals [*Richardson*, 1987]. More recent modeling work has shown that if substantial focusing of the ridge push torque occurs along the northern collisional boundaries (specifically along the Himalayan and New Guinea segments), then the first-order intraplate stress field in continental Australia can be explained without appealing to other, more poorly constrained tectonic forces such as subduction or basal drag forces [*Coblentz et al.*, 1995].

In light of this recent work, the purpose of the present study is to evaluate the sensitivity of the predicted intraplate stress field to several representations of the northern plate boundary forces and to understand the relative contribution of continental topographic forces. Whereas our previous work considered these topics for local parts of the the IAP [e.g., *Coblentz et al.*, 1995; *Sandiford et al.*, 1995], the present study extends these investigations by considering the contribution of these tectonic forces to the plate-scale intraplate stress field.

2. The Regional Intraplate Stress Field

The first-order pattern of the regional intraplate stress field of the IAP is relatively well defined by the available World Stress Map stress indicators [e.g., *Zoback*, 1992; *Coblentz et al.*, 1994; *Sandiford et al.*, 1995; and maps of the global intraplate stress field available at http://www-gpi.physik.uni-karlsruhe.de/wsm/maps]. The regional stress patterns, as defined by the $S_{H_{max}}$ orientations, are characterized by a smooth transition from a roughly N-S orientation in the Indian subcontinent to NW-SE in the northeastern Indian Ocean to roughly E-W in western Australia. Three regions of particular interest include the continental regions of India and Australia and the central Indian Ocean.

The regional stress field of the Indian subcontinent is characterized by four provinces based on regionally consistent $S_{H_{max}}$ orientations: the midcontinent, the southern shield, the Bengal basin, and the Assam wedge [*Gowd et al.*, 1992]. In general, the $S_{H_{max}}$ orientation is NNE-ENE throughout central and northern India with a mean direction of about N23°E. This orientation is subparallel to the direction of compression expected from the forces present along the Himalayan collision, which resist the northward movement of the IAP. There is, however, a large amount of scatter in $S_{H_{max}}$ orientations throughout the Indian subcontinent, suggesting that some of the stress indicators reflect local sources of stress rather than the collisional tectonics.

The stress field in continental Australia is characterized by E-W compression in the western and eastern regions and N-S compression in the north [e.g., *Denham et al.*, 1979; *Lambeck et al.*, 1984; *Friedrich et al.*, 1988; *Denham and Windsor*, 1991]. This change in orientation is thought to be related to the resistance of the Indian Ocean-Australian plate to subduction along its northern margin [*Fitch et al.*, 1973] or to the position of Australia relative to the subduction zones along the northern IAP boundary [*Cloetingh and Wortel*, 1985, 1986]. The great Sumba earthquake of 1977 [*Stewart*, 1970], suggests the presence of a large slab pull force acting along the Sunda arc. Along the North West Shelf, $S_{H_{max}}$ is oriented roughly northeast in the Timor Sea region and nearly E-W in the Barrow-Dampier subbasin [e.g., *Hillis*, 1991; *Hillis and Williams*, 1992, 1993; *Hillis et al.*, 1997]. As in continental India, many of the observed stress data in continental Australia reflect a strong influence from local sources of stress. These local sources have the greatest effect on stress indicators based on shallow in situ stress measurements (such as hydraulic fracturing), many of which have been made at depths less than 1 km. Furthermore, stress orientations based on earthquake focal mechanisms may reflect the orientation of preexisting zones of weakness rather than the contemporary stress field.

The $S_{H_{max}}$ orientation in the oceanic regions between India and Australia changes smoothly from a N-S orientation off the southern coast of India, through a NW-SE orientation in the central Indian Ocean (roughly subparallel to the Java and Sumatra trenches), to a generally E-W orientation off the northwest coast of Australia.

A recent study that quantifies statistical trends in the $S_{H_{max}}$ orientation and observed stress regimes of the World Stress Map database stress indicators [*Coblentz and Richardson*, 1995] provides additional constraint on the predicted stress field from the modeling discussed below. Figure 1 shows the average stress regime and average $S_{H_{max}}$ orientations for stress indicators located in the IAP and reflects many of the generalizations about the intraplate stress field made above (see *Coblentz and Richardson* [1995] for a discussion of how the average stress regime was calculated and for further discussion). A number of general conclusions about the average stress regime and $S_{H_{max}}$ orientations within the IAP can be made on the basis of Figure 1: (1) The continental regions of India and Australia are primarily in a state of compression (TS and TF in Figure 1); (2) extensional stress regimes (NS and NF in Figure 1) are found primarily along the Southeast Indian Ridge and the Java–Sumatra subduction zones; and (3) the central Indian Ocean shows a mix of stress regimes but is primarily in a state of compression (TS and TF in Figure 1). The average stress regime and $S_{H_{max}}$ orientations for five subregions (continental India, Central Indian Ridge, Southeast Indian Ridge, central Indian Ocean, and continental Australia) are summarized in Table 1 and form the basis for the qualitative evaluation of the fit between the predicted and observed stress field used below.

3. Modeling Method

Predictions about the magnitude and orientation of the tectonic stresses in the IAP were made through a two-dimensional elastic finite element analysis of the intraplate stress field. The finite element grid consisted of 2527 constant-strain triangular elements composed of a network of 1374 nodes, which provided a spatial resolution of about 2° in both latitude and longitude throughout the plate. The details of this approach to modeling the intraplate stress field are discussed in detail elsewhere [e.g., *Richardson et al.*, 1979; *Richardson and Reding*, 1991; *Coblentz et al.*, 1995]. In addition to the tectonic forces discussed by *Cloetingh and Wortel* [1986] (e.g., ridge push, slab pull, basal drag, and compressive boundary tractions), we include the buoyancy forces resulting from lithospheric density variations associated with continental margins and elevated continental crust (see discussions by *Richardson and Reding* [1991] and *Coblentz et al.* [1994, 1995]). Forces due to the density moment from these density contrasts have been included in our plane-stress finite element code by incorporating a horizontal traction force, proportional to the horizontal gradient of the density moment [*Fleitout*, 1991; *Richardson and Reding*, 1991]. To ensure mechanical equilibrium, basal drag was applied only as needed to balance the net torque acting on the

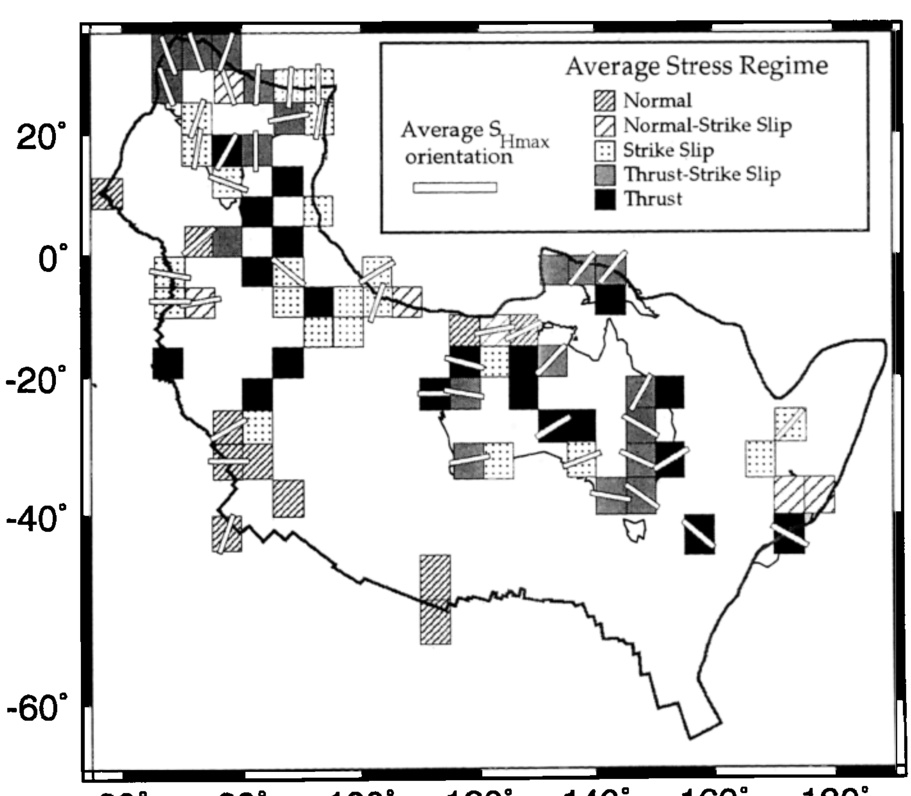


Figure 1. The stress regime α and average $S_{H_{max}}$ orientation within 5° × 5° bins, after *Coblentz and Richardson* [1995]. Average $S_{H_{max}}$ orientations are shown for bins containing more than one indicator.

Table 1. Summary of Stress Regime and $S_{H_{max}}$ Orientation Within the IAP

Location	Stress Regime	$S_{H_{max}}$ Orientation
Continental India	mixed, SS to TS	mixed, predominately N–S
Central Indian Ridge	NF to SS	E–W to NE–SW
Southeast Indian Ridge	NF	NE–SW, normal to ridge
Central Indian Ocean	SS to TF	N–S to NW–SE
Continental Australia	mixed, SS to TF	mixed, predominately E–W

Abbreviations for stress regime indicate the following: NF, normal; NS, normal-strike-slip; SS, strike-slip; TS, thrust-strike-slip; and TF, thrust. Abbreviations for $S_{H_{max}}$ orientation indicate directions (e.g., N–S = north–south).

plate (see discussion by *Richardson et al.* [1979]). At the outset we note that the sensitivity of the modeled stresses is limited to large-scale tectonic features with wavelengths of a few hundred kilometers and that the predicted stress magnitudes are calculated for a lithosphere of constant thickness (assumed in the present and stress concentrations may occur where variations in the lithospheric thickness are present. The principal sources of constraint for the predicted stresses in the modeling included the observed $S_{H_{max}}$ orientations and information about the observed stress regimes discussed above.

Although there is compelling evidence for distinct Indian and Australian plates, we have modeled the IAP as a single plate in the present study for two reasons. First, while significant deformation and shortening is observed between the Chagos–Laccadive and the Nintyeast Ridges (see, for example, the discussion by *Van Orman et al.* [1995]), there does not appear to be a significant change in $S_{H_{max}}$ orientation in this region, suggesting that tectonic stresses are effectively transmitted between the two plates. In addition, we are interested in comparing our predicted stress field with that of *Cloetingh and Wortel* [1985, 1986], who treated the IAP as a single plate.

4. Modeling Results

We have used four models to evaluate the relative contribution to the observed intraplate from the various tectonic forces acting on the IAP. Previous studies of the tectonic forces acting on the IAP have shown the ridge push torque to be of fundamental importance to the intraplate stress field [*Coblentz et al.*, 1995; *Sandiford et al.*, 1995]. Of the various tectonic forces, the ridge push force is the best understood and is reasonably well constrained by age and bathymetry data [e.g., *Turcotte and Schubert*, 1982]. Thus each of the models presented below has been designed to evaluate the influence of various boundary conditions in conjunction with the ridge push force. The first three models are used to evaluate the effect of boundary conditions representing the forces acting along the northern plate margin. A fourth model is used to evaluate the role of drag forces acting along the base of the plate. The set of force parameters (e.g., ridge push and collisional boundary forces) applied in each of the models is listed in Table 2. To facilitate evaluation of the role that continental topographic forces play in the intraplate stress field, the predicted stresses for each model are shown both with and without continental topographic forces. Table 3 is a qualitative evaluation of the fit between the predicted and observed $S_{H_{max}}$ orientations and stress regime for five subregions in the IAP (continental India, Central Indian Ridge, Southeast Indian Ridge, central Indian Ocean, and continental Australia). The fit of the predicted stress regime is based on a scale of 1 to 3, with a value of 3 corresponding to a fairly good fit to both the $S_{H_{max}}$ orientation and observed stress regime.

4.1. Model 1: Homogeneous Northern Boundary

In model 1, mechanical equilibrium was achieved by homogeneously fixing the entire northern margin. This is equivalent to assuming that all of the resistance to the ridge force is transmitted from the Pacific and Eurasia plates to the IAP plate along these boundaries, balancing any tendency for the boundary to be deflected. For the purpose of this first model, no differentiation was made between the collisional and subduction zone boundaries along the northern margin. The drag force acting on the base of the plate was assumed to be negligible in the model. The principal stresses for model 1 are shown in Figure 2. The intraplate stress field for this model is characterized by NE–SW trending compression throughout the plate in the case of no topographic forces and significant modulation of this trend in the continental areas when topographic forces are applied. Without topographic forces the maximum stress magnitude is about 18 MPa and is located along the northern boundary and in western Australia. In the continental areas of India the stresses are oriented NE–SW and have a magnitude of about 7 MPa, with no significant stress focusing along the Himalayan boundary. When topographic forces are applied, the largest compressive stresses are located south of Australia and have a magnitude of about 14 MPa. The stress field in continental India and Australia is characterized by a near-neutral state of stress with $S_{H_{max}}$ oriented N–S in both regions. In the absence of topographic forces,

Table 2. Tectonic Force Magnitudes and Relative Torque Contributions

Force	Magnitude, $\times 10^{12}$ N m^{-1}	Total Torque, $\times 10^{25}$ N m	Latitude, °N	Longitude, °E
Himalaya	4.0	6.3	0.0	–172.9
New Guinea	2.0	1.9	–39.8	–123.1
Banda	1.0	1.0	–15.7	–141.8
New Zealand	1.0	1.0	–46.5	–29.0
Sumatra	4.0	3.7	–19.0	–170.4
Java	–4.0	4.1	18.7	23.7
Solomon	–1.0	0.8	39.3	77.5
New Hebrides	–1.0	0.5	69.7	132.1
Tonga-Kermadec	2.0	2.5	–63.6	9.1
Ridge push	...	8.5	30.3	–34.5
Continental margins	...	2.6	–19.3	–173.7
Elevated continent	...	3.5	–12.6	94.0
Drag, model 4a	...	4.1	– 7.4	–102.8
Drag, model 4b	...	7.2	13.2	–28.8

Positive forces are directed toward the interior of the plate. Note: force magnitude of 1×10^{12} N m^{-1} is equivalent to a stress of 10 MPa (100 bars) across a plate with a thickness of 100 km. The magnitude of drag force produces a 0.1 MPa shear stress for an absolute plate velocity of 1.0 cm yr^{-1}.

the stress field predicted by model 1 is characterized by NE–SW compression throughout most of the plate and therefore yields satisfactory fit in continental India and along the Southeast Indian Ridge (Table 3). The addition of topographic forces improves the the fit in the continental regions of India and Australia. In particular, the small stress magnitudes predicted in these regions are consistent with the wide variation of the observed $S_{H_{max}}$ orientations. We note, however, that the dominant NE–SW orientation of the predicted stress field in the oceanic regions yields a poor fit to the data along the Central Indian Ridge and Central Indian Ocean. We therefore conclude that homogeneous boundary forces are an oversimplified representation of the forces acting along the northern plate margin.

4.2. Model 2: Fixed Collisional Boundaries

In model 2, only the continental collisional boundaries were used as boundary conditions to balance the ridge torque acting on the plate. Specifically, the Himalayan, New Guinea, and New Zealand segments were held fixed, while the other plate boundary segments (e.g., Sumatra, Java, Banda, Solomon, New Hebrides, and Tonga–Kermadec) remained free. These boundary conditions are equivalent to applying a force along the collisional boundaries proportional to the amount of displacement due to focusing of the ridge push torque along these margins. While still simplistic, these boundary conditions are a more plausible situation than those in model 1.

Table 3. Description and Ratings of the Finite Element Model

	Force Parameters				Model Fit					
Model	F_R	F_{CB}	F_{SB}	F_D	CI	CIR	SIR	CIO	CA	Figure
1	A	P	P	O	2,2	1,1	2,2	1,1	1,2	2
2	A	P	F	O	1,2	1,2	2,2	3,3	1,2	3
3	A	P	A	O	2,3	2,2	2,2	2,2	2,3	4
4	A	A	A	A	2,1	3,3	2,2	3,3	2,3	5
CW	A	A	A	A	1	3	2	2	2	...

For force parameters, letters indicate the following: A, applied force; P, pinned boundary; F, free boundary; O, force not applied; F_R, ridge push forces; F_{CB}, collisional boundary forces; F_{SB}, subduction zone forces; and F_D, drag forces. For fit to observed stresses, letters indicate the following: CI, Continental India; CIR, Central Indian Ridge; SIR, Southeast Indian Ridge; CIO, Central Indian Ocean; and CA, Continental Australia. Numbers indicate the following: 3, a fairly good fit to both $S_{H_{max}}$ and stress regime; 2, a fairly good fit to either $S_{H_{max}}$ or stress regime; 1, a moderate fit to either $S_{H_{max}}$ or stress regime; and 0, poor fit to both $S_{H_{max}}$ and stress regime. Numerical pairs designate respective fits for no topographic forces and applied topographic forces. Model CW is the modeling presented in the work of *Cloetingh and Wortel* [1985, 1986] with the same fit criteria applied. See text for discussion.

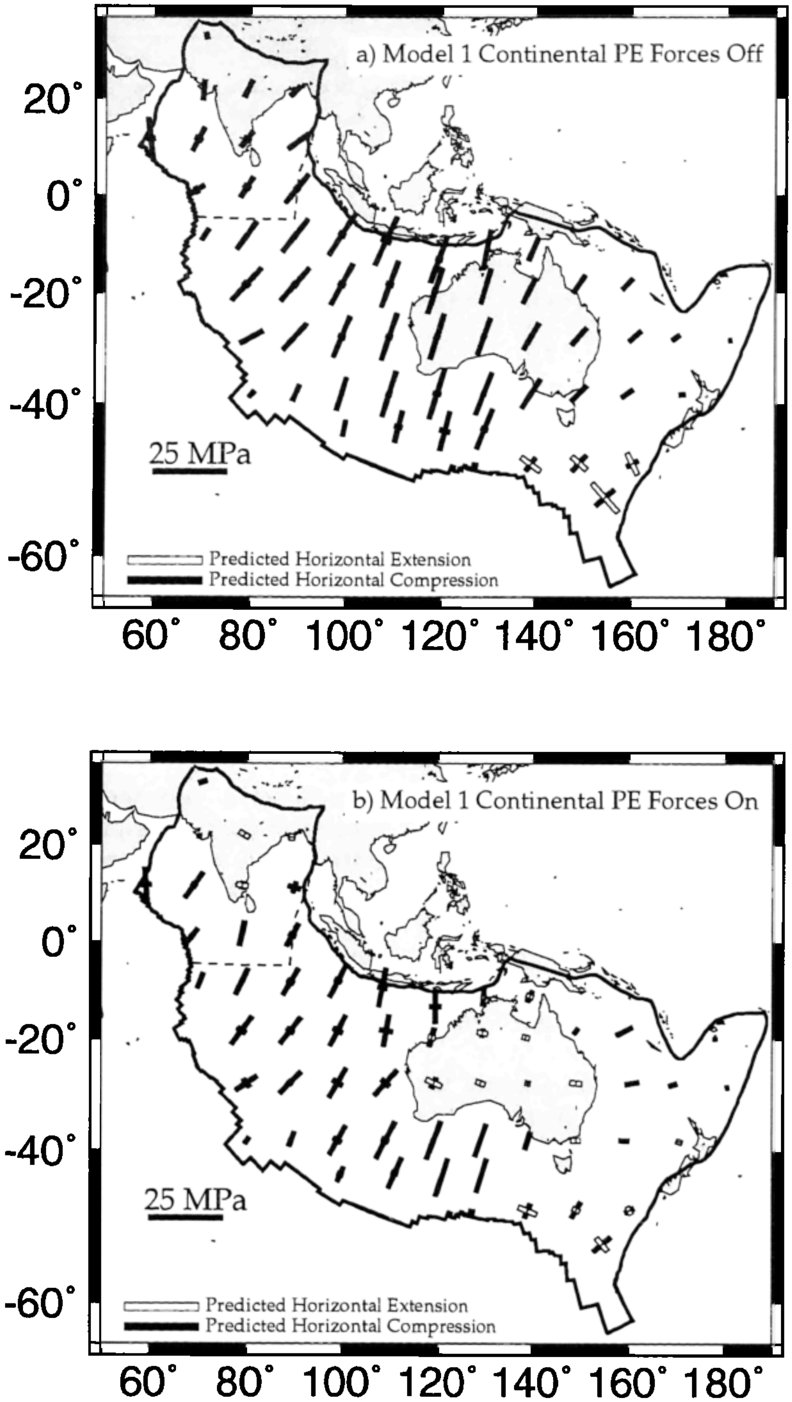
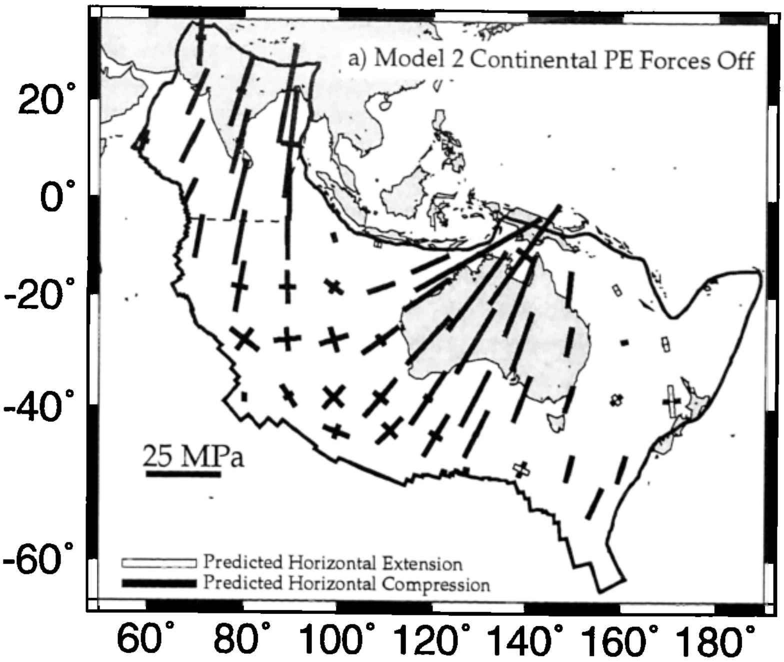


Figure 2. Predicted stresses for model 1. Ridge push torques acting on the plate are balanced by fixing the entire northern and eastern plate boundaries. Solid and open bars indicate nonlithostatic compression and tension, respectively. Predicted stresses throughout continental Australia are compressional (approaching 18 MPa), with $S_{H_{max}}$ oriented nearly uniformly NE–SW. See Table 3 for qualitative evaluation of fit between predicted and observed stresses.

The fixed segments produce considerable stress focusing (Figure 3) in the northern parts of continental India and Australia. The largest compressive stresses occur south of New Guinea, where stress magnitudes are close 50 MPa. As in model 1, the addition of topographic forces has the effect of reducing the predicted stress magnitudes in the continental regions of India and Australia (e.g., the maximum predicted compression in the case of applied topographic forces is 28 MPa, which is slightly more than half that predicted without applied topographic forces). In both cases the predicted stress magnitudes in the eastern part of the plate are



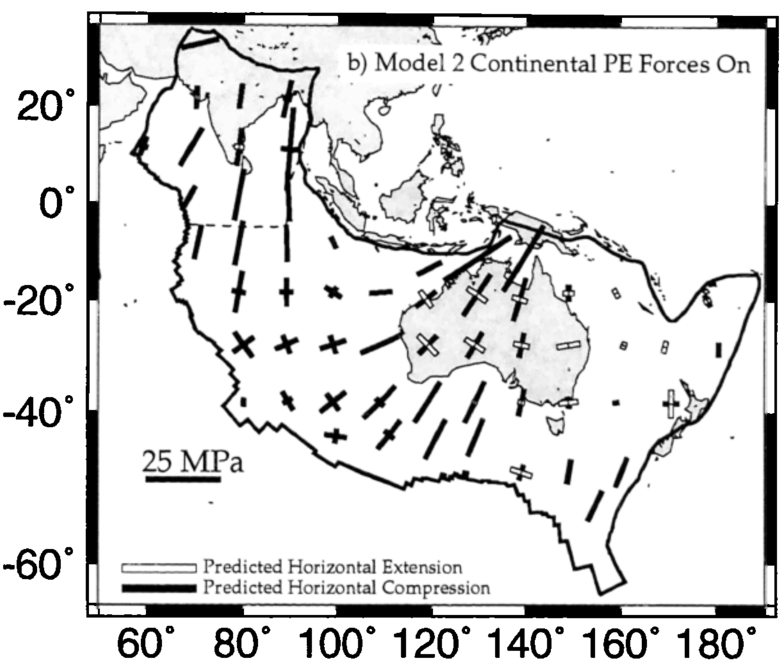


Figure 3. Predicted stresses for model 2. Ridge push torques are balanced by fixing the collisional boundary segments along the Himalayan, New Guinea, and New Zealand collisional boundary segments. Solid and open bars indicate nonlithostatic compression and tension, respectively. The predicted stress field is dominated by NE–SW compression (about 52 MPa) due to focusing of ridge push torque along the New Guinea boundary segment. See Table 3 for qualitative evaluation of fit between predicted and observed stresses.

small, suggesting that stress focusing is not as significant along the New Zealand boundary segment as along the Himalayan and New Guinea.

The predicted $S_{H_{max}}$ orientation for model 2 shows a great deal of variation across the plate. In general, $S_{H_{max}}$ is oriented N–S in continental India, E–W in the Central Indian Ocean, and NE–SW in continental Australia and is much more in agreement with the observed stress data than the predicted stress field in model 1. The predicted stress regimes and $S_{H_{max}}$ orientations for model 2 yield a much better fit to the observed data, particularly in the central Indian Ocean. Thus we conclude that if significant stress focusing occurs along the northern collision boundary segments in the IAP, the first-order features of the observed stress field can be explained in terms of the ridge push force.

4.3. Model 3: Applied Subduction Zone Forces

In model 3, subduction zone forces acting along the Sumatra, Java, Banda, Solomon, New Hebrides, and Tonga-Kermadec boundary segments were included in the force balance. A constant force per unit length of boundary segment was applied along the collisional boundary segments. We readily acknowledge that the exact magnitude of these boundary forces is poorly constrained, and we have chosen values to represent geologically plausible collisional tractions. In this model equilibrium was ensured by fixing the three collisional boundary segments: Himalayan, New Guinea, and New Zealand.

The predicted stresses for model 3 are shown in Figure 4. There are two principal differences between the

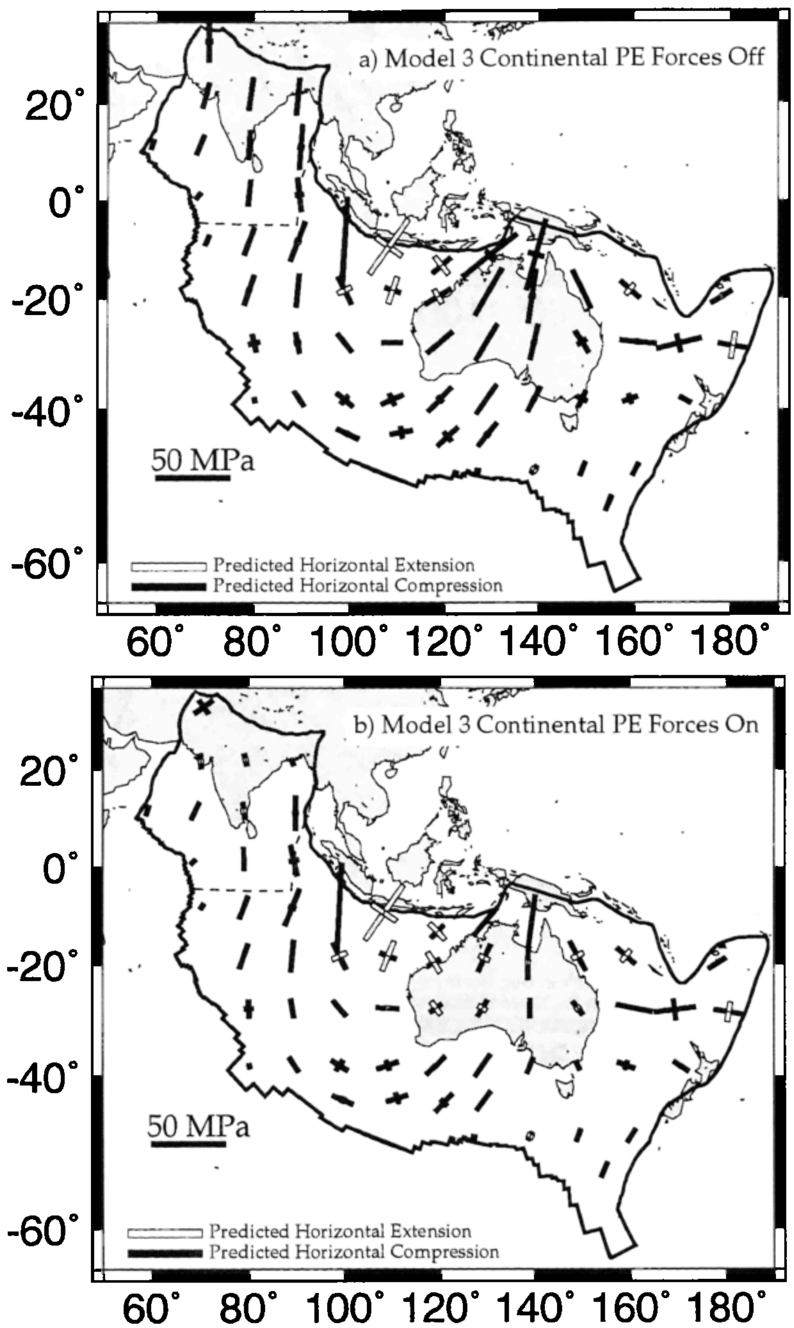


Figure 4. Predicted stresses for model 3. Representative forces applied along the northern and eastern boundary segments are as described in the text and listed in Table 2. Basal drag was used to balance the torque acting on plate. Solid and open bars indicate nonlithostatic compression and tension, respectively. The predicted stress field is characterized by large (77 MPa) compression south of India, localized tension (20 MPa) along the Java and Sumatra trenches, and small (20 MPa) compressive stresses throughout continental Australia. See Table 3 for qualitative evaluation of fit between predicted and observed stresses.

predicted stress field for models 2 and 3: (1) there is a reduction in the stress focusing effect due to forces applied along the northern plate margin (e.g., the predicted stress magnitude along the New Guinea boundary segment is only about half that predicted in model 2, 38 versus 50 MPa); and (2) while large tensional stresses are present along the Java-Sumatra subduction zone (about 45 MPa along the Java segment), the effect of these tensional stresses is localized along the trenches and does not extend a significant distance across the central Indian Ocean or along the North West Shelf of Australia.

As in the previous model, the inclusion of topographic forces produces significant differences in the predicted stress field in continental India and Australia. While topographic forces do not significantly change the predicted $S_{H_{max}}$ orientations in these regions, they do reduce the predicted stress magnitudes. For example, in continental Australia the predicted stress magnitudes are reduced from about 50 MPa to less than 25 MPa with the inclusion of topographic forces. In both continental India and Australia the small predicted stress magnitudes are consistent with the large variation in the observed $S_{H_{max}}$ orientations. That is, in regions where the horizontal stress field is nearly isotropic or the magnitudes of the two horizontal principal stresses are small, it is difficult to accurately measure $S_{H_{max}}$.

On the basis of the stresses predicted by model 3, we conclude that while tectonic forces associated with subduction along the northern plate boundary may have an important influence locally on the local stress field, they do not influence the broad-scale features of the IAP stress field. Rather, the overall intraplate stress field in the IAP seems to be dominately controlled by the combination of ridge push and collisional boundary forces.

4.4. Model 4: Comprehensive Boundary Forces and Basal Drag

Model 4 was used to evaluate the stresses predicted by a model with boundary forces applied along both collisional and subduction zone boundary segments. Since this force model does not produce a torque balance, a drag force was applied along the base of the plate to ensure mechanical equilibrium such that a plate velocity of 1.0 cm/yr produced a basal shear stress of 0.1 MPa. The force per unit length of boundary segment applied in this model and the amount of basal drag required to balance the torques acting on the plate are listed in Table 2.

The predicted stresses for model 4 are shown in Figure 5. The overall pattern of the predicted stress field is similar to model 3, particularly in the central Indian Ocean and continental Australia. We note, however, that the magnitude of the predicted stresses is much larger in many parts of the plate, for example, the predicted compression in the central Indian Ocean approaches 110 MPa. In other regions the predicted stress magnitudes remain small; for example, throughout the eastern part of the plate. We do note, however, that some stress concentration occurs in the central Indian Ocean. We note further that the trench-normal extension predicted by model 4 along the Central Indian Ridge is consistent with the observed intraplate stress field [see *Cloetingh and Wortel*, 1985, 1986]. As in model 3, large extensional stresses associated with the subduction zone forces along the Java–Sumatra trench are predicted but are not observed to extend far from the immediate vicinity of the plate boundary.

Because the basal drag required to provide mechanical equilibrium is different for the two cases with and without applied topographic forces, it is difficult to isolate the role of the topographic forces in the predicted stress field of this model. In both cases, however, the predicted stress field in continental India is dominately N–S compression with a magnitude approaching 50 MPa when topographic forces are included, and it is inconsistent with the observed data (see Table 3). In contrast, the magnitude of the predicted stresses in continental Australia are small, with both the stress regime and the $S_{H_{max}}$ orientation in substantial agreement with the observed data.

5. Discussion

Predictions about the intraplate stress field for four fundamental tectonic models of the IAP have been presented. These predictions demonstrate the relative contribution of the various tectonic forces acting on the plate. As was found in a previous study for continental Australia [*Coblentz et al.*, 1995], we find that the ridge push force, in conjunction with the boundary conditions used to represent the northern collisional boundary segments establishes the platewide first-order intraplate stress field with predicted stress magnitudes in most areas of the plate less than 25 MPa. Since the horizontal stresses associated with continental topography have a magnitude of less than 20 MPa [e.g., *Coblentz et al.*, 1994], they have the greatest effect on the predicted stress field in areas where the magnitude of the regional stresses is of the order of tens of megapascals. Indeed, we find that the inclusion of continental topographic forces significantly affects this first-order stress field, and the inclusion of the topographic forces improves the fit between the calculated and observed stresses. This is particularly true for the continental margin along the North West Shelf and the eastern passive margin of Australia [e.g., *Zhang et al.*, 1996]. Thus our results support the suggestion that these forces are an important source of stress even for plates dominated by boundary forces [e.g., *Fleitout and Froidevaux*, 1982, 1983; *Fleitout*, 1991].

We note, however, that in some parts of the plate (e.g., continental India and SE Australia) the fit between the predicted and observed stress fields remains poor for each of the models considered above. This is particularly true for India, where the uniform predicted stress field is at odds with the large amount of scat-

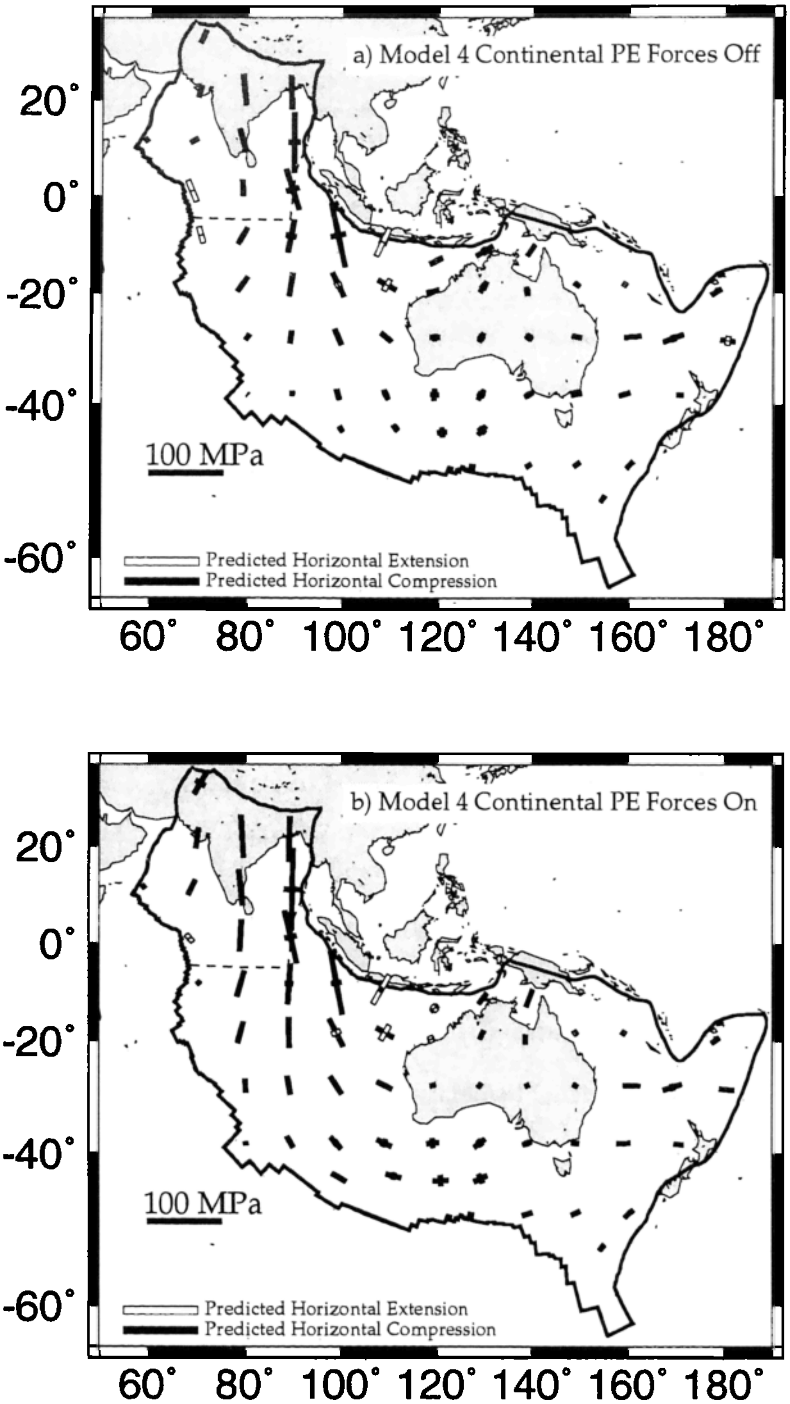


Figure 5. Predicted stresses for model 4. Topographic forces are included with the forces applied in model 3. Basal drag was used to balance torque acting on the plate. Solid and open bars indicate nonlithostatic compression and tension, respectively. Maximum compressive stresses approach 75 MPa; tension along the Java and Sumatra trenches is less than 25 MPa. See Table 3 for qualitative evaluation of fit between predicted and observed stresses.

ter in the observed $S_{H_{max}}$ orientation. Clearly, in these regions, other local sources of stress (which we have not included in our modeling) are influencing the stress field. Thus in these regions the first-order models used in the present study are oversimplistic. A more complete explanation of the nature of the intraplate stress field in these regions is the subject of more comprehensive modeling studies designed to take into account the small-scale tectonic features that may affect the magnitude and orientation of the stress field. Such studies may also help explain the considerable variation in the azimuth of P axes throughout continental Australia and India, as well as the predominance of strike-slip events in these areas.

The complexity of the observed intraplate stress field in the IAP may reflect the complex nature of the plate boundary opposite the ocean ridge. In other continental plates where ridge push force is considered to dominate the intraplate stress field (e.g., the North and South American plates), the nature of the plate boundary opposite the mid-ocean ridge system is relatively simple. The first-order tectonic forces acting along the western margins of these plates can be modeled as relatively uniform compression [e.g., *Richardson and Reding*, 1991; *Coblentz and Richardson*, 1996], which, in conjunction with the ridge push force, results in a fairly uniform stress field that corresponds well with the relative plate motion. In the IAP, however, the plate boundary opposite the mid-ocean ridge is not uniform, but rather a mixture of collisional and subduction zone segments. The main consequence of the complex northern boundary configuration seems to be significant stress concentration along the collisional segments, as well as a complex regional stress field (see discussion by *Coblentz et al.* [1995]). While the end result is that for the IAP there is little agreement between the ridge push torque, relative plate motion, and the observed stress field [*Richardson*, 1992], the modeling results presented above (in particular, model 2) demonstrate that ridge push exerts an important control on the character of the intraplate stress field in the IAP. These results are in substantial agreement with the observation that the nature of the intraplate stress field within the IAP is a consequence of the unique combination of tectonic forces acting on the plate [*Cloetingh and Wortel*, 1985, 1986; *Richardson*, 1987], with the observed stress field best explained in terms of a combination of ridge push and the forces acting along the northern boundary.

To facilitate a comparison of the predicted stresses discussed above and previous modeling studies, the criteria used to evaluate the models above were applied to the model presented by *Cloetingh and Wortel* [1986], and the results are included in Table 3. In general, the degree of fit for the predicted stresses of models 3 and 4 are quite similar to those of *Cloetingh and Wortel* [1986]. We note, however, that the intraplate stress magnitudes predicted in the present study are nearly an order of magnitude less than those predicted by *Cloetingh and Wortel* [1985, 1986]. This discrepancy is due primarily to the difference in the applied forces along the northern margin (in particular, the Java and Sumatra segments) and the Tonga-Kermadec segment. Because the magnitudes of the forces acting along these segments are poorly constrained, it is possible to fit the observed stress field with a number of models. Until the magnitudes of the boundary forces acting along these segments are further constrained, the models presented above should be considered a plausible alternative to those presented in the previous modeling studies of *Cloetingh and Wortel* [1985, 1986]. As we discussed above, the observed deformation in the central Indian Ocean is generally accepted to be related to interplate rather than intraplate deformation; thus extremely large tectonic stress should no longer be considered a requirement of the predicted stress field in the central Indian Ocean.

6. Conclusions

Although deformation within the Indo-Australian plate is well documented, the nature and origin of the tectonic stresses within the plate have proved difficult to constrain. The modeling work of *Cloetingh and Wortel* [1985, 1986] and *Richardson* [1987] demonstrated the important effect boundary forces have on the intraplate stress field but failed to explain the apparent enigma that, in contrast to most of the other plates, the intraplate stress field of the IAP does not appear to be dominated by ridge push forces. In this paper we have presented the results of a finite element analysis of the IAP intraplate stress field, which builds on the previous modeling studies through consideration of a wide range of plausible forces acting along the collisional and subduction zone boundaries and, importantly, the inclusion of forces due to other lateral density variations within the lithosphere, such as those associated with the continental margins and elevated continental topography.

The models presented above should be considered plausible representations of the ensemble of tectonic forces acting on the IAP and should offer an alternative to the conclusions drawn from previous modeling results of IAP intraplate stress field [e.g., *Cloetingh and Wortel*, 1985, 1986]. Within the assumptions made for the models presented above, the main conclusions of the present study are as follows: (1) The torque arising from the ridge push force is the principal contributor to the first-order intraplate stress field. (2) The orientations and magnitude of this first-order stress field are significantly modified by stress focusing along heterogeneous convergent boundaries. (3) Continental topographic forces significantly affect the predicted stress field in the continental regions of India and Australia, although other local stress sources may also be an important factor in explaining the observed stress field in these regions. (4) Tectonic forces associated with subduction and basal shear forces are not necessary to explain the broad-scale features of the observed intraplate stress field. (5) Low tectonic stress magnitudes (e.g., of the order of 20–40 MPa averaged over a 100-km-thick lithosphere) are predicted throughout most of the IAP, with the exception of the central Indian Ocean, where the stresses predicted by one model exceed 100 MPa.

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