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REGIONAL STRESS FIELD OF THE INDIAN PLATE

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Abstract. We have calculated the regional stress field in the Indian plate, implementing dependence of slab pull and ridge push on the age of the oceanic lithosphere in the finite element procedure. The high level of the calculated stress field (order of a few kbar) and the dominance of compression in the plate are consequences of the unique dynamic situation of the present-day Indian plate. The calculated stress field explains the concentration of intraplate deformation in the region of the Ninetyeast Ridge and yields insight into the variations in stress directions in the Australian continent.

Introduction

The Indian plate is characterized by a number of features which provide a unique opportunity to study the relation between the regional lithospheric stress field and tectonic deformation of oceanic and continental lithosphere. It contains a prominent example of intraplate deformation: the Ninetyeast Ridge (Stein and Okal, 1978). Furthermore, it is the only plate for which enough oceanic and continental focal mechanism data are available to examine regional consistency in intraplate lithospheric stress fields. The Indian plate is involved in two continental collision processes: on a large scale at the Himalayan suture and on a smaller scale in the Banda arc. Between these two areas, along the Sunda arc, there are significant variations in the age of the oceanic lithosphere (Heezen et al., 1977). The forces acting on the downgoing slab depend strongly on the age of the lithosphere (England and Wortel, 1980) and we have previously demonstrated the key importance of incorporating age-dependent plate tectonic forces in lithospheric stress modelling (Wortel and Cloetingh, 1981).

Models

The spherical surface of the Indian plate is approximated by an assembly of 485 triangular membrane elements with a quadratic displacement field (linear strain). The maximum grid size of the elements is 5 degrees. The stress calculations were made with the Aska package of finite element routines (Argyris, 1979). The model plate is taken to be elastic (Young's modulus E = 700 kbar and Poisson's ratio ν = 0.25), with a nominal thickness of 100 km.

The driving forces considered to act on the plate are the pull on the downgoing oceanic lithosphere at trenches (F_{sp}) and the ridge push (F_{rp}) which were calculated according to Richter and McKenzie (1978) and England and Wortel (1980). For age t less than 70 Ma, F_{sp} is proportional to $t^{3/2}$, with a somewhat weaker dependence on age for t in excess of 70 Ma. Following Wortel and Cloetingh (1981) we distributed the ridge push, which is the integrated value of a horizontal pressure gradient, over the corresponding part of the plate's area. Similarly, for t less than 70 Ma the ridge push F_{rp} (per unit width parallel to the ridge) depends linearly on lithospheric age. In our modelling of the Indian plate the ridge push was applied only to the lithosphere which originates from the presently active ridge system. Ages for oceanic lithosphere in the Indian plate are adopted from the map compiled by Heezen et al. (1977).

The resistive forces acting at oceanic trenches were incorporated after England and Wortel (1980) and Wortel and Cloetingh (1984), which account for both the buoyancy effect of the stable petrological stratification of the oceanic lithosphere (Oxburgh and Parmentier, 1977) and the shearing resistance along the plate contact and slab-upper mantle interfaces.

To ensure mechanical equilibrium the torques on the plate are required to vanish. Using India-Antarctica, India-Eurasia and India-Pacific pole positions given by Minster and Jordan (1978) this constraint enabled us to determine the average net resistive forces at the Himalayan collision zone (F_H), the suction force (F_{suc}) acting on the overriding Indian plate segment at the Tonga-Kermadec trench and the drag at the base of the lithosphere (σ_D), the magnitude of which was taken to be constant over the area of the plate's base. We obtained a value of $F_H = -1.9 \times 10^{12}$ Nm^{-1} (minus sign indicating resistance to plate convergence) and found that $F_{suc} = 10.9 \times 10^{12}$ Nm^{-1} (plus sign indicating the outward direction, towards the trench). Finally, we found that a constant resistive shear stress σ_D of 2.1 bar, acting at the base of the plate and in the direction derived from the position of the Antarctica-India plate pole, balances the torques. Notwithstanding the presence of the Australian and Indian continents, σ_D is not significantly different from the values of the shear stress at the base of the entirely oceanic Nazca plate (0-4 bar, see Wortel and Cloetingh, 1984).

Results and Discussion

The resulting horizontal stress field in the Indian plate is displayed in Fig. 1. The accuracy of the finite element solution was checked and confirmed by convergence tests and analysis of the internal reaction forces of the model.
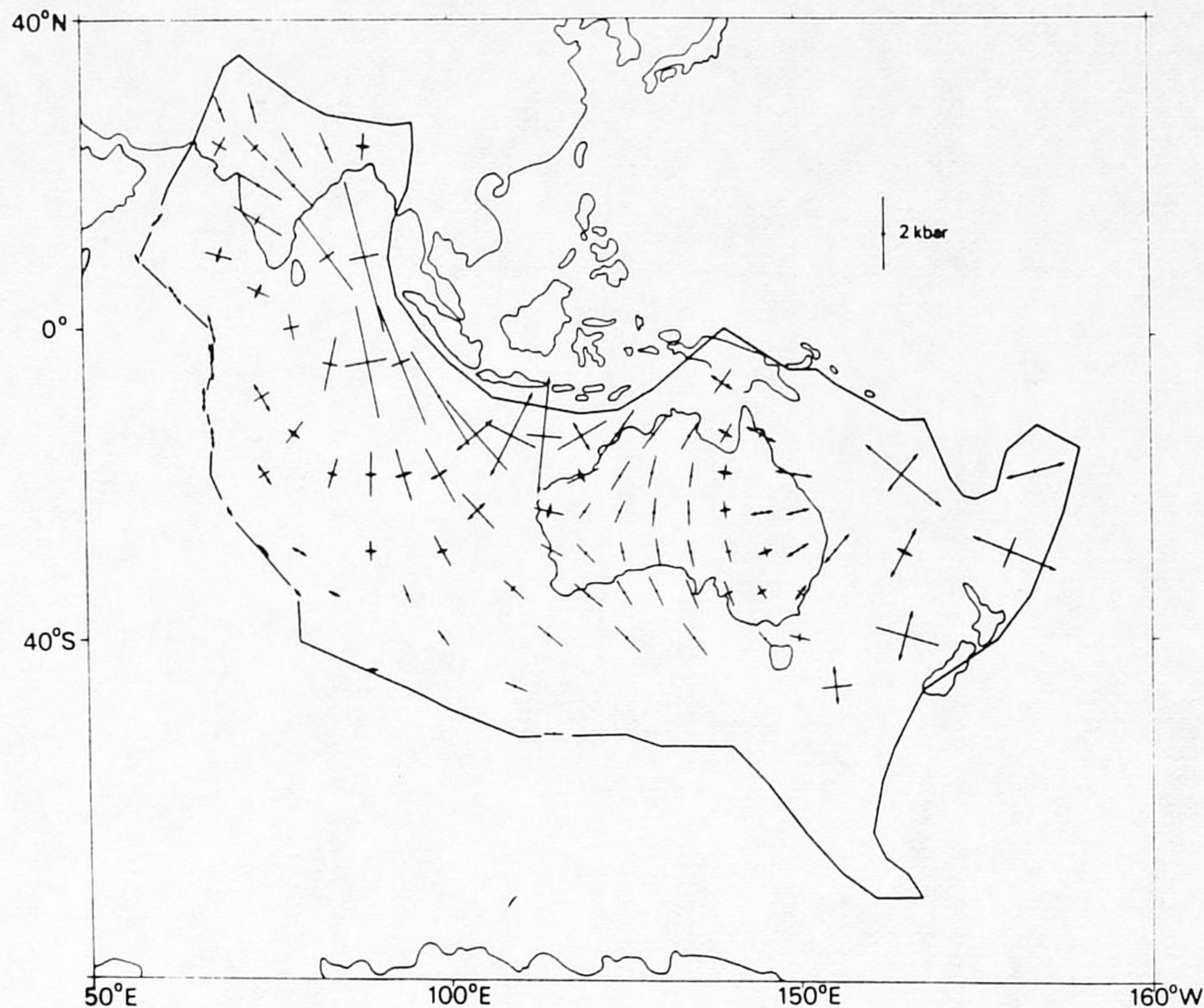
Fig. 1. Calculated principal horizontal deviatoric stresses in the Indian plate.
Symbols (↔) and (—⊥—) denote tension and compression, respectively.

Stress level

There are several factors that account for a high stress level in the Indian plate and that have been overlooked in stress modelling with constant boundary forces as employed by Richardson et al. (1979). Age variations, such as encountered along the Sunda trench, induce significant variations in net boundary forces. Coupled with an angular and curved geometry of the plate boundary, this is capable of concentrating stresses to kilobar levels. From the required torque balance we found that the Indian plate is undergoing a considerable net resistance at the Himalayan collision zone. Richardson et al. (1979), however, specified the magnitude of the resistance at continental collision zones a priori by imposing upper limits of the order of 100 bar on the induced stresses, which seems to imply a serious underestimate of F_H. Apart from at the Himalayan contact there is also considerable net resistance at other large segments of the convergent boundaries of the Indian plate. This applies in particular to the Banda arc and to the northwestern part of the Sunda arc. In combination with the ridge push, these features explain why compression is the dominant stress mode in the plate.

A recent very detailed study of depths of oceanic intraplate bending earthquakes by Ward (1983) gives strong independent evidence for the existence of intraplate stresses of a few kbar in a more general sense.

From the above we conclude that the exceptionally high level of the present-day regional stress field of the Indian plate is a transient feature which results from the unique dynamic situation in which the Indian plate now finds itself.

The Indian subcontinent and the Indian Ocean W. of the Ninetyeast Ridge

Fault plane solutions in different regions of the Indian subcontinent summarized by Scheidegger and Padale (1982) show a dominant N-S oriented compressive stress field. Fault plane solutions in the intensively studied Koyna region (Scheidegger and Padale, 1982) have confirmed this general pattern. These data are consistent with a stress field in which maximum compression acts horizontally NW-SE, as inferred from our modelling.

The calculated stress field in the area west of the Indian Peninsula has a roughly N-S directed tensional and E-W oriented compressional character. In this context, it is interesting to note that the Chagos Bank area is characterized by normal fault seismic events on an E-W fault plane (Bergman and Solomon, 1980).

The calculated stress field in the area adjacent to the Southeast India Ridge is characterized by tension parallel to the spreading ridge. This is consistent with the results of a recent focal mechanism study of Bergman et al. (1984). Their analysis showed the existence of a high level of near ridge seismicity and a hitherto unexplained consistent orientation of T-axes subparallel to the ridge axis (see Fig. 2).

The Ninetyeast Ridge area

For this area our modelling shows a concentration of compressive stresses with a magnitude larger than stress levels calculated by us for any other part of the Indian plate. This applies in particular to the northern segment of the Ninetyeast Ridge area, where the compressive resistance associated with Himalayan collision and subduction of young lithopshere off the northern part of the Sunda arc are focused. These findings provide a consistent explanation for the concentration of seismic activity in the Ninetyeast Ridge area, in particular for the occurrence of events of magnitudes greater than 7 along the northern tip (Stein and Okal, 1978). They also elucidate the significant brittle deformation by high-angle reverse faulting (Weissel, pers.comm., 1981) in oceanic crust, recorded in seismic reflection data from the southern part of the Bengal fan, and the occurrence of broad, hitherto rather puzzling, basement undulations (Weissel et al., 1980).

Minster and Jordan (1978) have demonstrated that closure of the Africa-India-Antarctica triple junction requires internal deformation of the Indian plate. These authors showed that observed rates and directions around the Indian Ocean are compatible with convergence between the western and eastern parts of the Indian plate along the northern part of the Ninetyeast Ridge, which is corroborated by our calculated regional stress field in the area.

The Java-Sumatra trench

The calculated stress field displays significant variations along the strike of the Sunda arc. Compression occurs seaward and parallel to the Sumatra trench segment, consistent with the fault plane solution of event 12 given in Fig. 2. Off Java, where stress orientation data are absent, the calculated stress field shows extension perpendicular to the trench. The change from a compressive stress field parallel off Sumatra to a tensional stress field normal to Java is caused by the contrast in the age of the subducted lithosphere under Sumatra (40-70 Ma) and Java (140 Ma). Following the Sunda arc in an easterly direction underthrusting of continental shelf occurs from just west of Flores onwards. A seismic event studied in that area by Ward (1983) shows evidence for a raised neutral surface compatible with a regional compressive stress field.

As demonstrated for the Peru-Chile trench (Wortel and Cloetingh, 1984), lateral variations in the component of the regional stress field perpendicular to the trench greatly influence the style of trench tectonics.

Australia and surrounding areas

Evidence from earthquake focal mechanism studies indicate that large parts of the Australian continent are in a state of horizontal compression (Denham et al., 1979; Lambeck et al., 1984). Based on observational evidence and modelling of gravity and topography, Lambeck et al. (1984) have suggested a magnitude of the
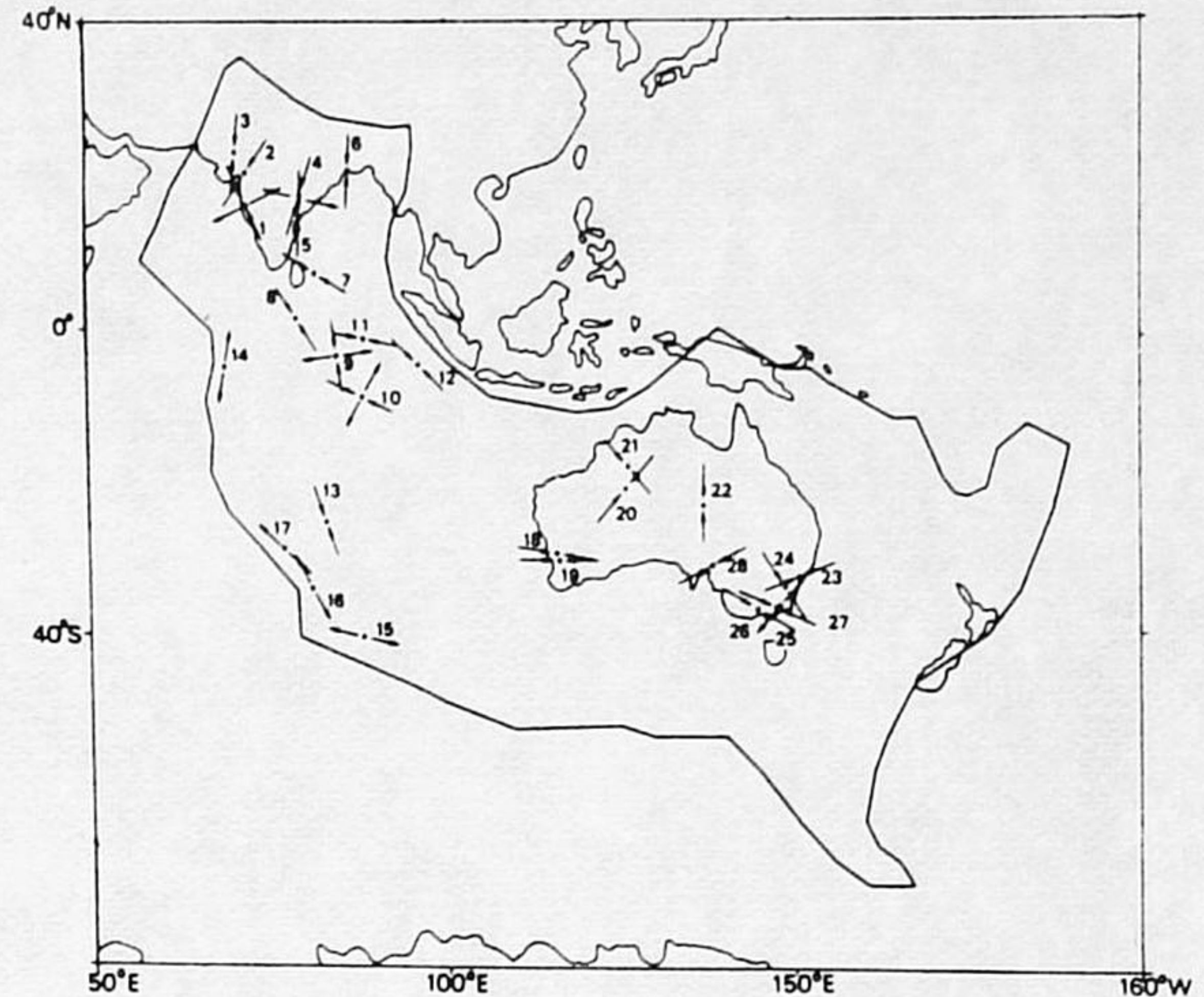

Fig. 2. Intraplate focal mechanism stress orientation data for the Indian plate obtained from the following sources:
1-6: Scheidegger and Padale (1982); 7-12: Stein and Okal (1978); 13-14: Sykes and Sbar (1974); 15-17: Bergman et al. (1984); 18-25: Denham et al. (1979), 26-28: Lambeck et al. (1984). Events with locations coinciding with fracture zone have been excluded. P and T axes point inward and outward, respectively.

order of 1-2 kbar for the regional stress field. As shown in Fig. 2 the observed principal stress orientations are in different directions in different regions of the continent. In essence, the stress field varies from E-W compression in S.W Australia to N-S compression in central Australia. In S.E Australia a more complex state of stress (including one case of tensional stress) has been observed (Lambeck et al., 1984).

Our modelling shows that the rotation of the stress field in the Australian continent is primarily the consequence of its geographic position relative to the surrounding trench segments and the variation of the forces acting on the downgoing slab in each of these. The state of compression in west and central Australia is induced by the action of resistive forces at the Himalayan and Banda arc collision zones. The predicted occurrence of a tensional component in the stress field in east Australia is induced by the action of a pull exerted on the downgoing slab in the New Hebrides trench and the suction force active on the Tonga-Kermadec plate boundary. Furthermore, the action of net tensional forces along these segments and the presence of a regional tensional stress field off the New Hebrides and off the Tonga-Kermadec trench, is consistent with the observed (Ward, 1983), exceptionally low position of the neutral surface off the New Hebrides and the occurrence of back-arc spreading off Tonga-Kermadec.

Significant variations in the regional stress field occur along the Australian passive margins. This is particularly evident along the eastern Australian margin. Here the calculated regional stress field is oriented roughly perpendicular to the margin and varies from NW-SE tension to NE-SW tension and finally to E-W compression, as one

goes from north to south along the margin. Therefore, the eastern Australian margin offers a unique case to analyse the relation between variations in regional stress field and local flexural stress fields induced by sediment loading on the margin (Cloetingh et al., 1982), and their effect upon the tectonic style and subsidence of passive margins.

The existence of a compressional palaeostress field of a few kbar in Australia and the role of compressive forces in orogeny has been pointed out by Lambeck (1983), based on a study of the deformation of Australian intra-cratonic basins. Our modelling shows that such stress fields can be generated by plate tectonic forces.

Conclusions

The high level of the calculated regional stress field, the dominance of compression and the strong variations in stress directions in different areas of the Indian plate, are consequences of its unique dynamic situation. The calculated stress field elucidates the intraplate tectonics in the Ninetyeast Ridge area. The observed variation in stress directions in the Australian continent and the magnitude of the stress field are directly associated with the forces on the Indian plate.

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