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Stress in the Indo-Australian plate

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Abstract

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We modelled the state of stress in the Indo-Australian plate in order to investigate quantitatively variations observed in tectonic style. The numerical procedure incorporates the dependence of slab pull and ridge push on the age of the oceanic lithosphere. Estimates are presented for the average net resistive forces at the Himalayan collision zone, the suction force acting on the overriding Indo-Australian plate segment at the Tonga–Kermadec trench and the drag at the base of the lithosphere.

Our modelling shows a concentration of compressive stresses of the order of 3–5 kbar in the Ninetyeast Ridge area; the effects of the compressive resistance associated with Himalayan collision and subduction of young lithosphere off the northern part of the Sunda arc are focused in this region. The stress field as calculated gives a consistent explanation for the observed concentration of seismic activity (Stein and Okal, 1978) and significant deformation in the oceanic crust (Weissel et al., 1980; McAdoo and Sandwell, 1985) in the area.

The calculated stress field in the area adjacent to the Southeast and Central India ridges is characterized by tension parallel to the spreading axis. This explains the concentration of near-ridge normal faulting seismicity (with *T*-axes subparallel to the spreading ridge) in the Indian Ocean as recently observed by Bergman et al. (1984) and Wiens and Stein (1984).

The regional stress field along the strike of the Sunda arc varies from compression seaward of and parallel to the Sumatra trench segment, to tension perpendicular to the Java–Flores segment. This explains the selective occurrence of well developed grabens seaward off the Java–Flores segment of the trench, observed by Hilde (1983).

Our modelling shows that the observed rotation of the stress field (Denham et al., 1979) in the Australian continent is mainly the consequence of its geographic position relative to the surrounding trench segments and the variations of the forces acting on the down-going 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 joint occurrence of high levels of compression in the plate's interior and normal faulting seismicity in the near-ridge areas, is a transient feature unique to the present dynamic situation of the Indo-Australian plate.

Introduction

The Indo-Australian plate is characterized by a number of features which provide a unique opportunity for studying the relationship between intraplate stress fields and the tectonic deformation of oceanic and continental lithosphere: (1) The Ninetyeast Ridge is the most prominent known example of intraplate deformation (Stein and Okal, 1978). (2) The Indo-Australian plate is involved in a large scale continental collision process at the Himalayan suture. (3) It is the only plate in which compressional folding of oceanic lithosphere has been reported (Weissel et al., 1980; McAdoo and Sandwell, 1985; Zuber and Parmentier, 1985). (4) Nearly all known strong ($M_s > 7$) oceanic intraplate earthquakes which are not associated with continental margins or plate

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boundaries, are located in the zone stretching across the equatorial Indo-Australian plate (Wiens, 1986). (5) A major part of the off-ridge normal faulting seismicity recently observed and attributed to relaxation of thermo-elastic stresses (Bergman et al., 1984; Wiens and Stein, 1984) occurs in the oceanic lithosphere close to spreading ridges in the western part of the plate. As noted by Wiens and Stein (1984) and Wiens (1986), this mechanism does not explain why this phenomenon is so overrepresented in the Indo-Australian plate.

The presence of substantial and reliable oceanic and continental focal mechanism data sets recently obtained by various investigators (Stein and Okal, 1978; Denham et al., 1979; Bergman et al., 1984; Wiens and Stein, 1984; Bergman and Solomon, 1985) makes a systematic examination of regional consistency in the intraplate lithospheric stress field possible. We have modelled the regional stress field in the plate in order to gain a better understanding of the occurrence of so many unique and at first sight even contradictory observations in this plate.

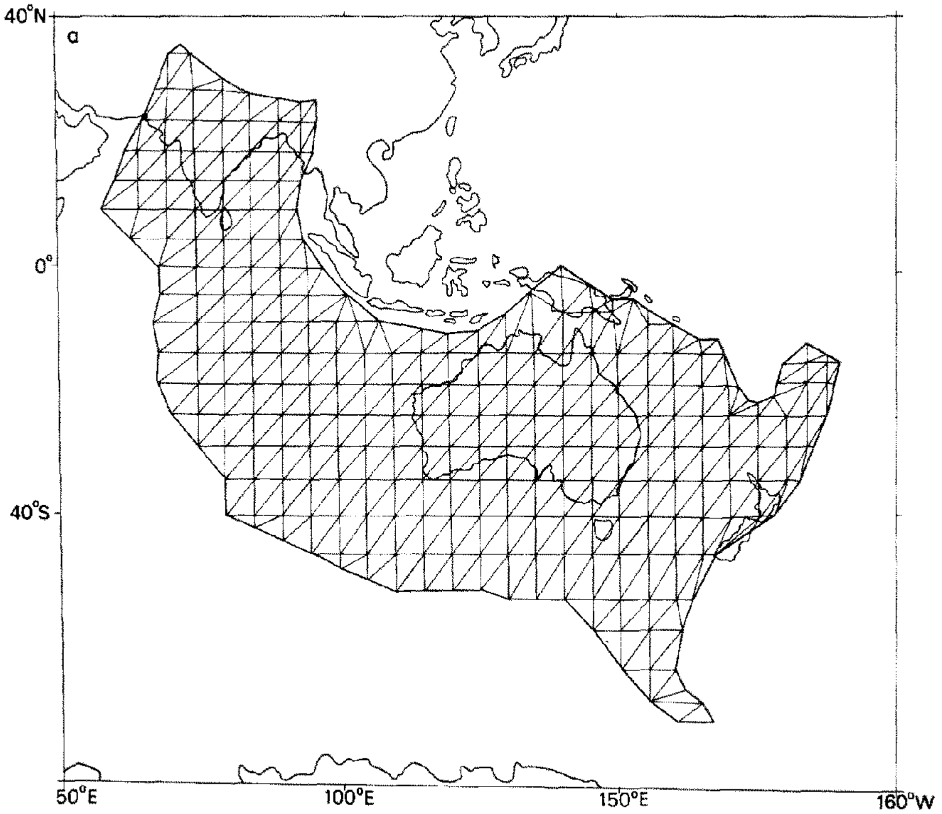
In general, as Chapple and Tullis (1977) have pointed out, the complexity of the boundary forces acting on lithospheric plates may imply intraplate stress fields of considerable magnitude. More specifically, we have, in previous work, demonstrated the key importance of incorporating age-dependent plate-tectonic forces in lithospheric stress modelling (Wortel and Cloetingh, 1981). The calculated regional stress field of the Indo-Australian plate presented in this paper proves to correlate closely with the high level of intraplate deformation and intraplate seismicity. Furthermore, the results of our calculations give better insight into the observed spatial variations in tectonic style in different areas of the Indo-Australian plate.

Modelling

The stress field in the Indo-Australian plate is calculated using finite-element techniques. This method allows adequate incorporation of age-dependent driving forces (Wortel and Cloetingh, 1981, 1983; Cloetingh et al., 1982) and plate configurations (Richardson et al., 1979; Wortel and Cloetingh, 1981, 1985; Cloetingh and Wortel, 1985) in lithospheric stress modelling. In contrast with our previous model studies of stresses in entirely oceanic plates (Wortel and Cloetingh, 1981; 1983), the modelling of the Indo-Australian plate demands the incorporation of forces associated with continental collision and suction at overriding plate segments.

Finite-element procedure

We calculate the regional stress field using an uniform elastic plate with a (relaxed) Young's modulus $E = 7 \times 10^{10}$ N m^{-2} (Anderson and Minster, 1980) and Poisson's ratio $\nu = 0.25$. Figure 1a shows the finite-element mesh used in the analysis. We have approximated the spherical surface of the Indo-Australian plate by an assembly of 485 triangular membrane elements with a quadratic displacement field (linear strain). The number of degrees of freedom is 2104. The maximum size of the elements is five degrees. We ignore vertical stresses in the plane stress approximation adopted here and calculate the horizontal stress field in the lithosphere which is integrated over the lithospheric thickness. The resulting field represents the non-lithostatic state of the lithosphere. The outcome of our stress calculations can be easily related to estimates of the integrated depth-dependent lithospheric strength that follow from studies of the mechanical properties of the oceanic lithosphere (Goetze and Evans, 1979; Wiens and Stein, 1983). In the present paper we display stress values derived (from the values integrated over the lithospheric thickness) for an elastic plate with uniform elastic properties and a thickness of 100 km. We emphasize that this is a reference thickness value only. As we assume uniform elastic properties in the plate we ignore possible differences between the mechanical properties of oceanic and continental parts of the Indo-Australian plate which imply depth-dependent features (e.g., variations in elastic thickness), vertical stresses and isostatic compensation processes. Attempts to incorporate these effects have to wait until more progress is made in determining the rheological structure of continental



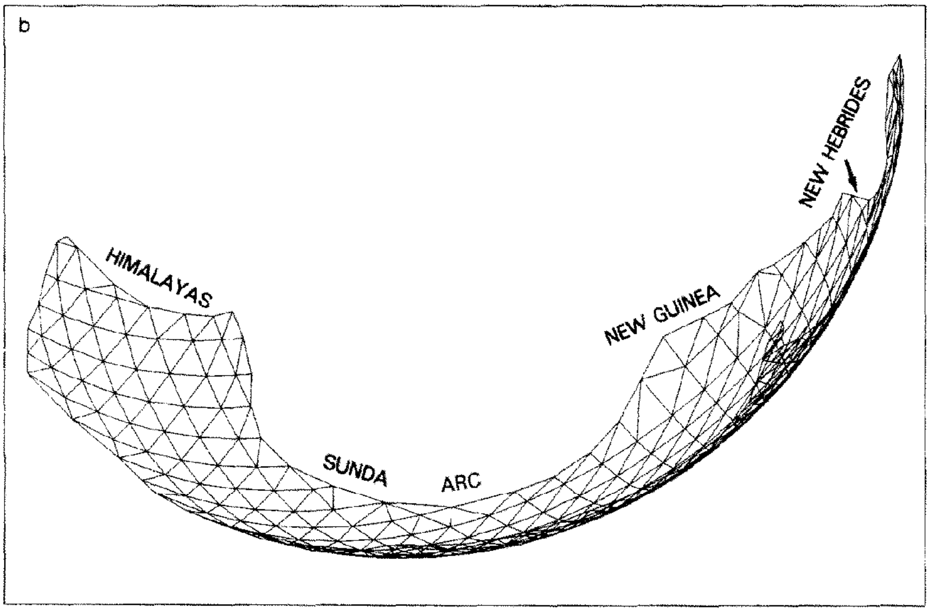


Fig. 1. a. Finite-element mesh of the Indo-Australian plate. The spherical surface of the plate is approximated by an assembly of 485 triangular membrane elements with a quadratic displacement field (linear strain). b. Illustration of quality of the approximation of the spherical shell by the assembly of flat elements.

lithosphere. At present, estimates of the equivalent elastic thickness of the continental lithosphere vary considerably (e.g., Quinlan and Beaumont, 1984; Stephenson, 1984). This is in part, because they are dependent on the adopted models of the original emplacement and the subsequent evolution of the topographic loads.

The stress calculations are made with the Aska package of finite-element routines (Argyris, 1979). Figure 1b illustrates the quality of the approximation of the spherical shell by the assembly of flat elements. The accuracy of the finite element solution was confirmed both by convergence tests and by analysis of the internal reaction forces of the model.

Force modelling

The regional stress field in the Indo-Australian plate is assumed to be determined by the plate-tectonic forces, shown schematically in Fig. 2. The forces considered to act on the plate are the driving forces F_{sp} (slab pull) and F_{rp} (ridge push), the resistive forces F_{tr} (resistance at the trench and in the subduction zone), F_H (average net resistance associated with the Himalayan collision zone), F_{dr} (drag or shear stress σ_d at the base of the plate, integrated over the area of the base of the plate) and the suction force F_{suc} (Forsyth and Uyeda, 1975) acting on overriding Indo-Australian plate segments. F_{tr} consists of two parts: One part (F_{cb}, compositional buoyancy) is associated with the petrological stratification of the oceanic lithosphere created during the spreading process at an oceanic ridge. This stratification implies a density structure which contributes a gravitationally stable component to the lithosphere–asthenosphere system. As such it counteracts the gravitationally unstable component resulting from the cooling and thermal contraction of the lithosphere, which is represented by the slab pull F_{sp}. The other part (F_{sh}) represents shearing forces acting along the contact between the downgoing plate and the overriding plate and along the boundaries of the subducted slab in the upper mantle. In addition to these plate-tectonic forces, there are also forces acting on the lithosphere which induce more local stresses. A number of these mechanisms has been reviewed by Turcotte and Oxburgh (1976). In plates that are involved in collision or subduction processes, however, plate-tectonic forces dominate the stress field. For this reason, the effect of topography, and flexure induced by sediment loading is not taken into account in the present analysis.

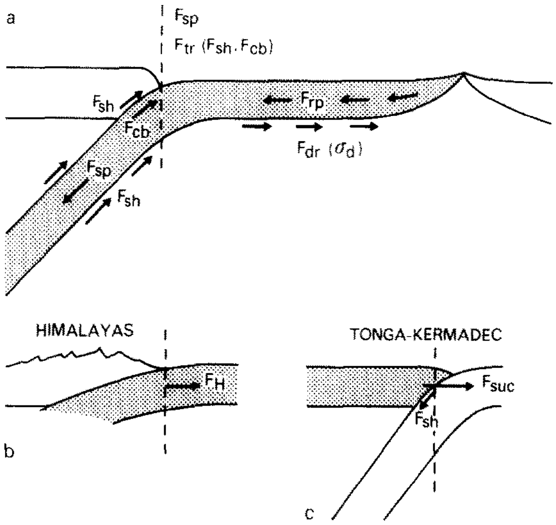


Fig. 2. Forces acting on the Indo-Australian plate (shaded).
a. General representation. Driving forces: F_{rp} (ridge push), F_{sp} (slab pull). Resistive forces: F_{dr} (drag force at the base of the plate, σ_d is shear stress), F_{tr} (resistance at the trench and in the subduction zone). F_{tr} is composed of two parts: F_{cb}, the compositional buoyancy force and F_{sh}, the shear forces along plate contact and along slab's upper and lower boundaries. F_{sp} and F_{tr} are modelled as boundary forces acting in the cross section of the plate near the trench (dashed line). Special cases are shown in (b) and (c).
b. Himalayan suture zone. The dynamics are modelled by an average net resistive force F_H acting on the Indo-Australian plate (in the indicated cross section).
c. Tonga-Kermadec subduction zone. Here the Indo-Australian plate is the *overriding* plate. The forces are represented by the suction force F_{suc} on the overriding plate and the shear force F_{sh}, along the plate contact. Again both forces are incorporated as if they act in a vertical cross section of the plate.

The slab pull and ridge push are calculated according to Richter and McKenzie (1978) and Wortel (1980). It can be shown (McKenzie, 1969) that the slab pull per unit width along the trench depends on the thickness L of the subducted slab according to $F_{sp} \sim L^3$. It is generally agreed upon that L depends on the square root of the age (t) of the lithosphere for $t < 70$ Ma (e.g., Parsons and

McKenzie, 1978). Hence for these ages, $F_{sp} \sim t^{3/2}$. Due to the reduced rate of thickening for $t > 70$ Ma, the age-dependence is somewhat weaker for old lithosphere. Similarly, for $t < 70$ Ma, the ridge push F_{rp} (per unit parallel to the ridge) was found to be linearly dependent on the lithospheric age near the trench (England and Wortel, 1980; Richter and McKenzie, 1978). The ridge push acting on the oceanic lithosphere should be considered to be the integrated value of a horizontal pressure gradient over the distance from the ridge (Lister, 1975). Thus, as in our previous work on lithospheric stress modelling (e.g., Wortel and Cloetingh, 1981, 1983, 1985), we distribute the total ridge push over the corresponding area of the plate. The lithospheric ages needed to calculate F_{rp} and F_{sp} are taken from the maps compiled by Heezen et al. (1977) and Sclater et al. (1980). The slab pull F_{sp} depends on the convergence rate v_c (McKenzie, 1969; Richter and McKenzie, 1978) and the dip angle ψ of the descending slab as $F_{sp} \sim v_c \sin \psi$. Hence F_{sp} varies linearly with v_z, the vertical velocity of the subducted slab. It was shown by Wortel (1980) that present-day subduction zones display the following characteristics: $2 \leqslant v_z \leqslant 3.5$ cm/yr for oceanic lithosphere younger than 65 Ma and $4 \leqslant v_z \leqslant 6$ cm/yr for oceanic lithosphere older than 100 Ma. In our model we calculated F_{sp} using $v_z = 3$ cm/yr and $v_z = 5$ cm/yr as representative values for these age groups and linearly interpolated velocities for the intermediate ages. This approach is equivalent to (but more convenient than) incorporating the local values of v_c and ψ taken from, for example, the RM2-relative velocity model (Minster and Jordan, 1978) and the distribution of intermediate and deep earthquakes in all subduction zones involved, respectively.

The resistive forces F_{tr} acting at the trench are incorporated following England and Wortel (1980) and Wortel and Cloetingh (1985), who found a total resistive force of -7×10^{12} N m^{-1} per unit width along the trench. The buoyancy effect of the stable petrological stratification of the oceanic lithosphere (F_{cb}), according to Oxburgh and Parmentier's (1977) model, accounts for -4×10^{12} N m^{-1}. The remaining resistance of -3×10^{12} N m^{-1} is attributed to shearing forces acting along the plate contact and the interface between the slab and the surrounding upper mantle. In our approach (see also Wortel and Cloetingh, 1983) of calculating intraplate stress fields we choose to use internally consistent parameters (in agreement with pertinent data sets) to making a variable parameter study.

To ensure mechanical equilibrium, the sum of the torques on the plate is required to be zero. Using India–Eurasia, India–Antarctica and India–Pacific pole positions given by Minster and Jordan (1978) this constraint enables us to determine the average net resistive forces at the Himalayan collision zone F_H, the suction force F_{suc} which is assumed here to act on the overriding Indo-Australian plate segment at the Tonga–Kermadec trench and the drag σ_d at the base of the lithosphere, the magnitude of which was taken to be constant over the area of the plate's base. From the torque balance equations we obtain a value of $F_H = -1.9 \times 10^{12}$ N m^{-1} (with the minus sign indicating resistance to plate convergence) and find that $F_{suc} = 10.9 \times 10^{12}$ N m^{-1} (with the plus sign indicating the outward direction, towards the trench). Finally, we find 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. It is interesting to note that despite the presence of the Australian and Indian continents, the *average* value of the drag 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, 1985). Further evidence for the presence of low shear stresses at the base of lithospheric plates has recently been given by Davis and Solomon (1985) using global torque balance modelling. Upper bounds of 3.5 bar for the basal shear stress acting on plates with spreading velocities of 10 cm/yr, have been inferred from surveys of oceanic intraplate seismicity by Wiens and Stein (1985) and Stein and Okal (1986).

Figure 3 shows the distribution of the *net* boundary forces acting on the plate. Inward pointing arrows indicate the trench areas where the resistance at the trench is greater than the pull on the downgoing plate. In such cases there is a

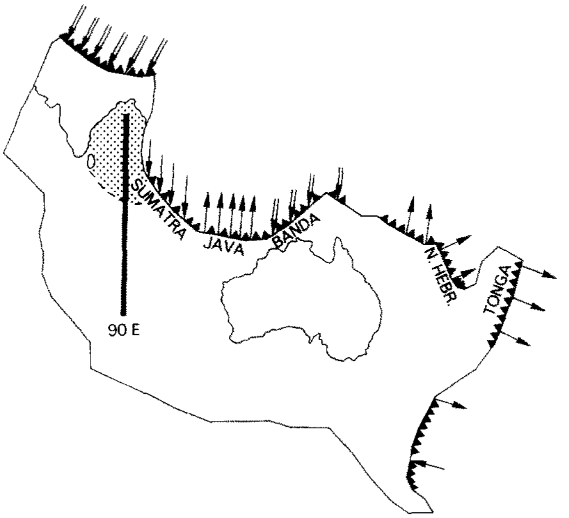


Fig. 3. Distribution of *net* boundary forces acting on the plate. Inward pointing arrows indicate the trench areas where the resistance at the convergence zone is larger than the pull on the downgoing plate, which results in a *net* resistance. Double arrows indicate the regions with' net resistive forces at the Himalayan and Banda arc collision zones. Outward pointing arrows indicate the trench areas where the slab pull associated with subduction of old oceanic lithosphere is larger than the trench resistance. The length of the arrows schematically indicates the direction, not the magnitude, of the forces at the plate boundaries.

net resistance at the plate boundary. This situation occurs off Sumatra, where young lithosphere is being subducted and at the Himalayan and Banda collision zones. Outward pointing arrows indicate the trench areas where the slab pull associated with the subduction of old lithosphere is larger than the trench resistance. The latter situation is found in particular at the Java segment of the Sunda arc trench system.

Regional stress field: general features

The calculated horizontal stress field in the Indo-Australian plate is displayed in Fig. 4. Three conspicuous features of the stress field stand out: the high level of the calculated stresses, the dominance of compression in the plate and the concentration of stresses in the Ninetyeast Ridge–Bay of Bengal areas.

Stress level

The stresses in the Indo-Australian plate are an order of magnitude greater than those we have calculated using the same technique for the Nazca plate. The latter are in the order of 500 bar (see Wortel and Cloetingh, 1985). There are several factors that account for a high stress level in the Indo-Australian plate but have not been taken into account in the stress modelling with constant boundary forces as employed by Richardson et al. (1979). Age variations, such as those encountered along the Java–Sumatra trench, induce significant variations in the net boundary forces. This is capable of concentrating stresses to kilobar levels, when combined with the angular and curved geometry of the plate boundary. This has been demonstrated previously for the Farallon plate, immediately before its fragmentation into the Nazca plate and the Cocos plate (Wortel and Cloetingh, 1983). From the torque balance we calculated that the Indo-Australian plate is undergoing a considerable net resistance at the Himalayan collision zone. In contrast, Richardson et al. (1979) 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. This leads to a much lower estimate of F_H. There is also considerable net resistance at other large segments of the convergent boundaries, particularly the Banda arc collision zone and the northwestern part of the Sunda arc, where young oceanic lithosphere is subducted. In combination with the ridge push, these features explain why compression is the dominant stress mode in the plate.

In a more general sense Ward's (1983) recent very detailed study of depths of oceanic intraplate bending earthquakes provides strong independent evidence for the existence of intraplate stresses of the order of kilobars. He found that neutral surfaces associated with downbending and subduction of young lithosphere are elevated as much as 15 km above those at boundaries where old oceanic lithosphere is subducted. He, therefore, concluded that regional stress fields could be of the same order of magnitude as stresses induced by bending. These have been shown previously to be of the order of a few kilobars (Caldwell et al., 1976; McAdoo et al., 1978). The deformation of the lithosphere prior to subduction has also been

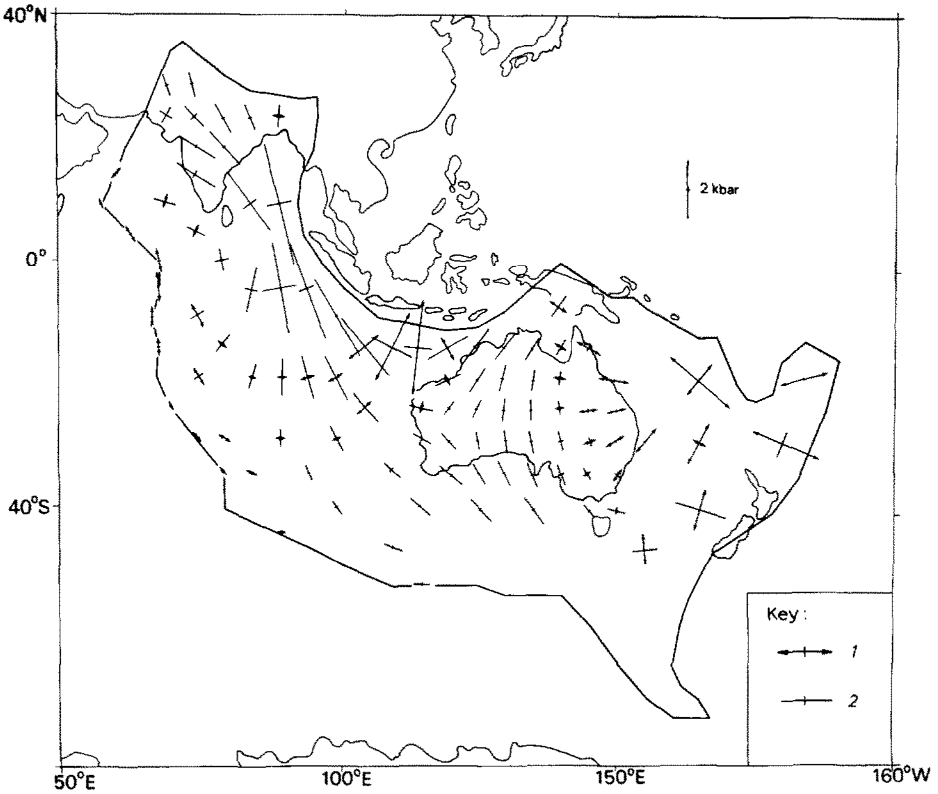


Fig. 4. Regional stress field in the Indo-Australian plate calculated on the basis of the force distribution given in Fig. 3. Plotted are principal horizontal non-lithostatic stresses averaged over an uniform elastic plate with a reference thickness of 100 km. Symbols *1* and *2* denote tension and compression respectively. The length of the arrows is a measure for the magnitude of the stresses.

interpreted in some instances to imply in-plane stresses of a few kilobars (McAdoo et al., 1978). Furthermore, studies of the formation of sedimentary basins also indicate horizontal (tensional) stresses of a few kilobars (Cloetingh and Nieuwland, 1984; Houseman and England, 1986).

From the foregoing, it is concluded that in a general sense the occurrence of intraplate stresses at the kilobar level ought not to be excluded a priori in lithospheric modelling.

The actual stress level in a plate depends on its specific tectonic setting, which in general is subject to changes during its evolution. This was clearly illustrated by our modelling of the stress state of the Nazca plate and its predecessor the Farallon plate which showed that stresses of the order of 2–3 kbar in the Farallon plate were relaxed after its break-up at 30 Ma to a stress level of the order of 500 bar in the present-day Nazca plate (Wortel and Cloetingh, 1983, 1985).

The *present day* Indo-Australian plate is characterized by a number of observed features that are consistent with an anomalous high level of the regional stress field. The plate is characterized by an exceptionally high level of intraplate seismicity (Bergman and Solomon, 1980). Several earthquakes in the Bay of Bengal have been found to be at depths corresponding with the strong core of the strength envelopes calculated for oceanic lithosphere (Stein, 1984), which implies stresses of 4–5 kbar. Broad basement undulations seen in seismic reflection profiles for the same area have also been interpreted as deformation resulting from compressive forces equivalent to stresses of the order of several kilobars (Weissel et al., 1980). Studies of the departures from isostatic equilibrium in several tectonic provinces within Australia have lead to the postulation of in-plane stresses of at least 1–2 kbar (Lambeck, 1983; Lambeck et al., 1984). The connection between observations and stress calculations will be more fully discussed in the following regional sections.

From the above, we conclude that the exceptionally high level of the present-day regional stress field of the Indo-Australian plate is a transient feature resulting from the unique dynamic situation in which the Indo-Australian plate is now involved.

Stress orientation

The directions of the stresses vary widely over the different areas of the Indo-Australian plate. Figure 5 is a compilation of intraplate focal mechanism stress orientation data for the Indo-Australian plate. Focal depths and other specifications of the data are listed in Table 1. A comparison of Figs. 4 and 5 demonstrates an overall agreement between the directions of the regional stress field as calculated and those observed in the plate. In the following section we concentrate on the variations in orientations and magnitude of the stress field in different areas of the Indo-Australian plate.

Regional stress-field: spatial variations

In order to discuss the relationship between observed variations in tectonic style and spatial variations in stress we divide the Indo-Australian plate into the following five areas: (1) the Indian subcontinent and the Indian ocean west of the Ninetyeast Ridge, (2) the area adjacent to the Central- and Southeast India Ridges, (3) the Ninetyeast Ridge and the Bay of Bengal, (4) the Java–Sumatra trench system and (5) Australia and peripheral areas.

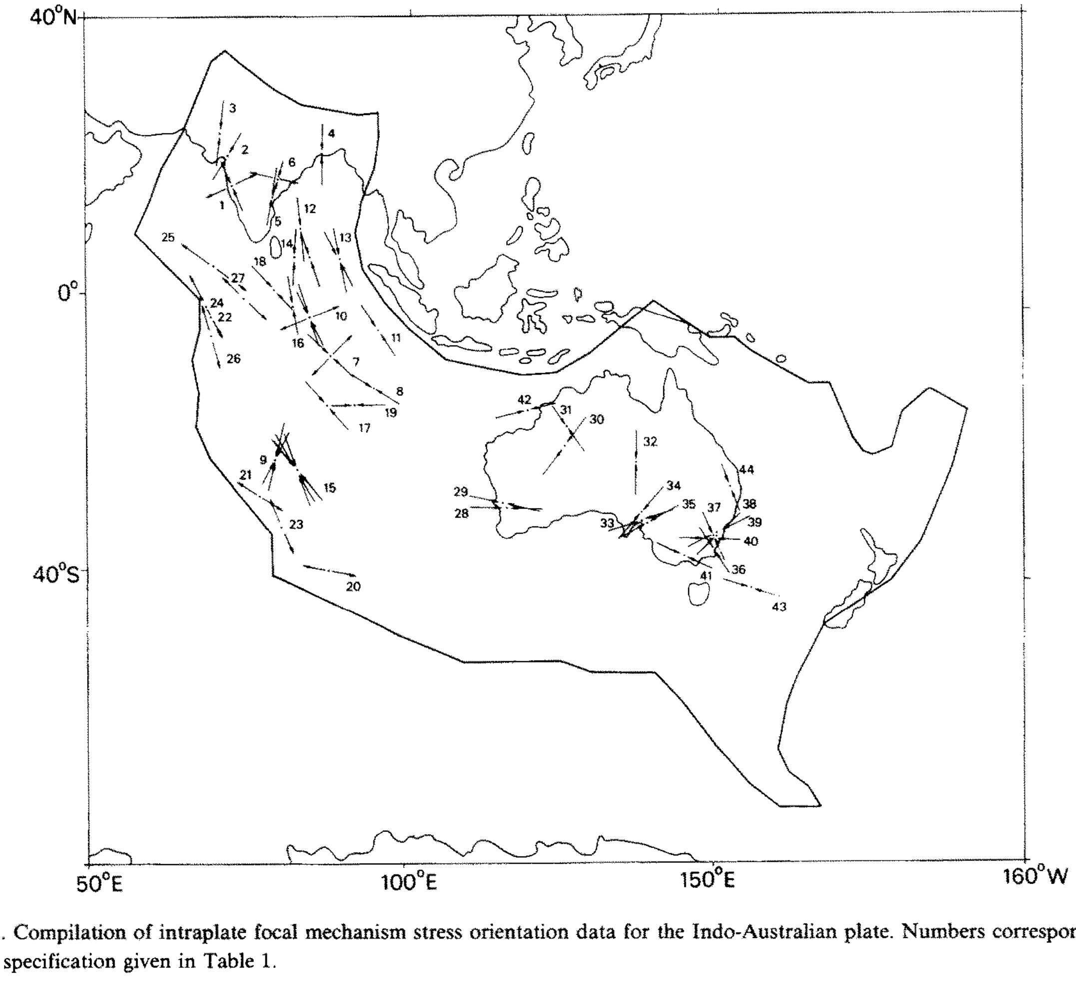


Fig. 5. Compilation of intraplate focal mechanism stress orientation data for the Indo-Australian plate. Numbers correspond to the event specification given in Table 1.

TABLE 1

Stress orientation data from focal mechanism studies

Event No.	Date	Lat. (°N)	Long. (°E)	m_b	M_s	Depth (km)	P-axis		T-axis		Reference
							strike	dip	strike	dip	
1	Dec. 10, 1967	17.5	73.7	6.0		12	157	17	63	17	Scheidegger and Padale (1982)
2	Mar. 23, 1970	21.7	73.0	5.4		3	210	6	108	64	Chandra (1977)
3	Oct. 24, 1969	24.8	72.4	5.3		15	8	0	98	55	Chandra (1977)
4	Apr. 15, 1964	21.7	88.0	5.5		36	181	22	55	55	Chandra (1977)
5	Mar. 27, 1967	15.6	80.1	5.4		17	188	20	8	70	Chandra (1977)
6	Apr. 13, 1969	17.9	80.6	5.3		33	195	20	102	9	Chandra (1977)
7	May 25, 1964	−9.08	88.89	5.7	6.0	17	312	1	42	6	Bergman and Solomon (1985)
8	Oct. 31, 1965	−14.22	95.27	5.3	5.4	24	120	9	26	22	Bergman and Solomon (1985)
9	Sept. 14, 1968	−24.45	80.41	5.4		3	27	3	141	83	Bergman and Solomon (1985)
						4	195	26	342	60	Bergman and Solomon (1985)
10	Oct. 10, 1970	−3.56	86.19	5.8	6.3	27	334	2	64	1	Bergman and Solomon (1985)
						39	163	2	254	27	Bergman and Solomon (1985)
11	Jun. 26, 1971	−5.18	96.90	5.9	6.4	29	326	4	234	29	Bergman and Solomon (1985)
12	Nov. 24, 1972	11.67	85.34	5.2	5.2	27	354	6	112	77	Bergman and Solomon (1985)
13	Apr. 07, 1973	7.00	91.32	5.8	6.6	13	349	7	259	1	Bergman and Solomon (1985)
						6	154	4	245	8	Bergman and Solomon (1985)
14	Aug. 30, 1973	7.15	84.33	5.8	5.2	27	1	3	262	68	Bergman and Solomon (1985)
15	Jun. 25, 1974	−26.02	84.30	6.1	6.6	23	321	13	219	43	Bergman and Solomon (1985)
						18	149	7	264	75	Bergman and Solomon (1985)
						13	339	7	238	55	Bergman and Solomon (1985)
16	Aug. 3, 1978	−0.93	84.24	5.5	5.5	39	351	8	171	82	Bergman and Solomon (1985)
17	Dec. 2, 1981	−15.76	88.39	5.7	5.5	23	140	2	40	82	Bergman and Solomon (1985)
18	Apr. 23, 1967	1.6	80.2	4.9	4.3	30	317	25	137	65	Stein (1984)
19	Jun. 3, 1978	−16.24	93.03	5.5		11	269	13	13	32	Stein (1984)
20	Oct. 8, 1968	−39.8	87.7	6.0	5.8	11	280	77	100	13	Wiens and Stein (1984)
21	Nov. 2, 1976	−29.35	77.66	5.8	6.5	14	323	78	121	11	Wiens and Stein (1984)
22	Mar. 31, 1970	−3.8	69.7	5.5		12	105	45	12	3	Wiens and Stein (1984)
23	Sep. 19, 1975	−34.76	81.85	6.0	6.1	19	158	73	338	17	Wiens and Stein (1984)
24	Nov. 17, 1973	−1.60	69.83	5.5	5.1	19	247	50	154	3	Wiens and Stein (1984)
25	Dec. 12, 1981	4.89	70.15	5.5		15	37	63	305	1	Bergman and Solomon (1984)
26	Oct. 2, 1957	−6.3	69.7		5.7	14	255	4	345	4	Wiens (1986)
27	Feb. 29, 1944	0.3	75.4		7.2	12	221	0	314	83	Wiens (1986)
28	Oct. 14, 1968	−31.58	117.00		6.9	5	291	13	20	50	Denham et al. (1979)
29	Mar. 10, 1970	−31.11	116.47		5.9	1	282	16	23	39	Denham et al. (1979)
30	Mar. 24, 1970	−22.05	126.01		6.7	15	218	24	58	64	Denham et al. (1979)
31	May 6, 1978	−19.55	126.56		6.2	17	324	6	226	54	Denham et al. (1979)
32	Aug. 28, 1972	−24.74	136.92		6.2	7	181	1	271	39	Denham et al. (1979)
33	Apr. 16, 1977	−32.44	137.96		3.8	5	254	17			Lambeck et al. (1984)
34	Aug. 30, 1977	−31.06	138.47		4.2	10	41	0			Lambeck et al. (1984)
35	Sep. 28, 1977	−32.30	139.31		4.0	15	60	25			Lambeck et al. (1984)
36	May 18, 1959	−36.22	149.64		4.2	15	327	10	79	64	Denham et al. (1979)
37	Jul. 4, 1977	−34.65	148.89		4.8	13	154	0	64	38	Denham et al. (1979)
38	May 21, 1961	−34.55	150.5		5.6	19	46	34	212	55	Lambeck et al. (1984)
39	Mar. 29, 1973	−34.17	150.32		5.5	21	64	6	323	65	Denham et al. (1979)
40	May 6, 1977	−35.03	149.02		3.8	5	271	10	174	39	Denham et al. (1981)
41	Dec. 2, 1977	−37.88	144.27		4.4	21	292	25	112	65	Denham et al. (1981)
42	Apr. 23, 1979	−16.66	120.16			34	78	13	258	77	Denham (in prep.)
43	Nov. 25, 1983	−40.45	155.51		6.0	18	106	29	276	61	Denham (1985)
44	May 15, 1977	−27.44	152.65			10–14	338	37			Rynn (1984)

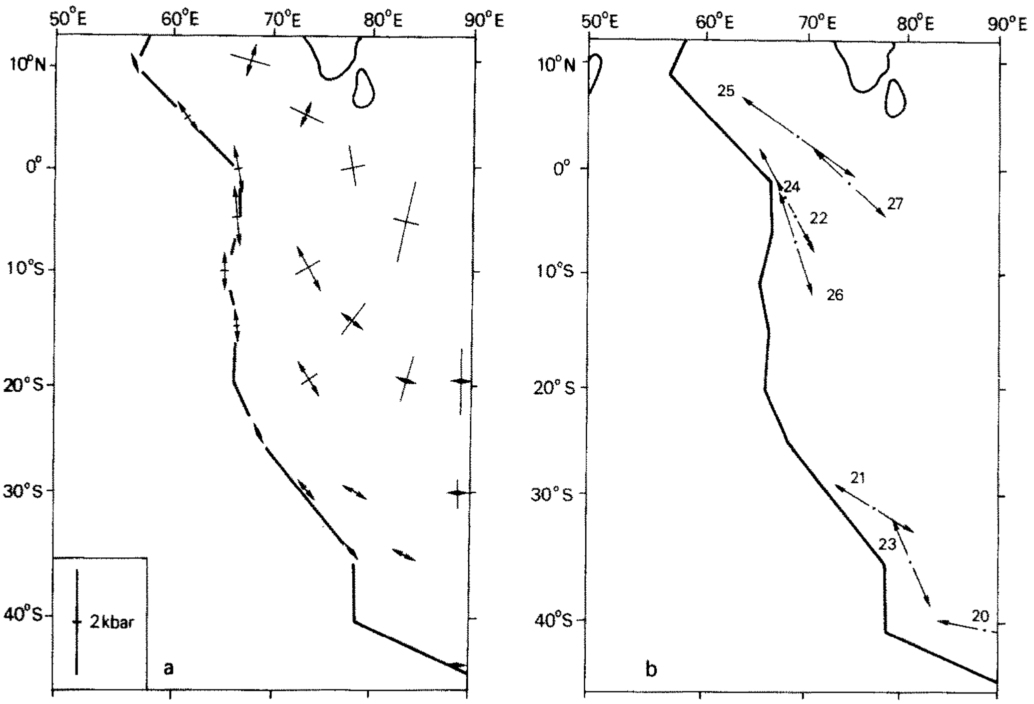


Fig. 6. Tensional stresses in the area adjacent to the Central- and Southeast India Ridges. a. Calculated stress field taken from Fig. 4. b. Stress orientation data from focal mechanism studies by Bergman and Solomon (1984), Wiens and Stein (1984) and Wiens (1986). Events at locations corresponding to fracture zones have been excluded. Numbers correspond to events listed in Table 1.

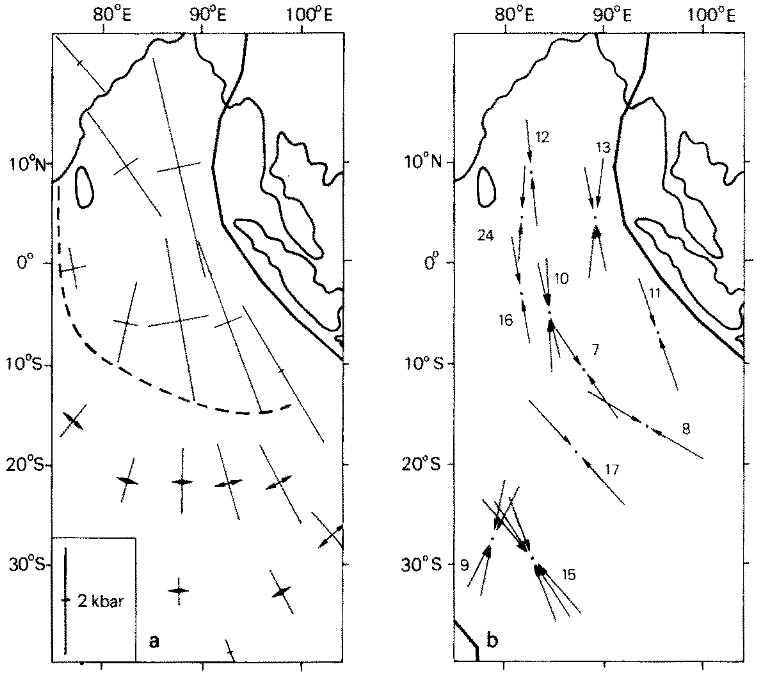


Fig. 7. Regional stress field in the Ninetyeast Ridge area and the Bay of Bengal. a. Calculated stress field taken from Fig. 4. The dashed line is the southern limit of the observed deformation in the northern Indian Ocean (Geller et al., 1983). b. The orientation of maximum horizontal compressive stress inferred from a focal mechanism study by Bergman and Solomon (1985) using the criterion of Raleigh et al. (1972). Figure conventions as in Fig. 6b.

The Indian subcontinent and the Indian Ocean west of the Ninetyeast Ridge

Fault-plane solutions in different regions of the Indian subcontinent given by Chandra (1977) and 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) confirm this general pattern. These data are in rough agreement with the stress field inferred from our modelling in which maximum compression acts horizontally in a direction which is more NW–SE oriented.

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. The Chagos Bank area is characterized by normal faulting seismic events on an E–W fault plane (Bergman and Solomon, 1980). Recently, Wiens (1986) studied the historical seismicity in the Chagos area and found that the area has been the site of recurrent high-rate seismicity. The tensional stress orientations in the Chagos area (age 35 Ma) are conform with the stress directions obtained from studies of intraplate seismicity in young oceanic lithosphere (ages less than 20 Ma) in areas close to the Southeast- and Central India ridges (Bergman and Solomon, 1984; Wiens and Stein, 1984). It should be noted, however, that the calculated stress field does not agree with the focal mechanisms at sites of events 25 and 27 (see Fig. 6).

The high level of the stress field is manifested by earthquakes with depths corresponding to rupture close to the core of the mechanically strong part of the lithosphere as well as by the occurrence of magnitude 7 events (Wiens and Stein, 1983; Stein, 1984).

Tension parallel to the Central- and Southeast India ridges

The calculated stress field in the area adjacent to the Central- and Southeast India ridges (Fig. 6a) is characterized by tension parallel to the spreading ridge. This is consistent with the results of recent focal mechanism studies by Bergman et al. (1984), Wiens and Stein (1984) and Bergman and Solomon (1984). Their analysis showed the existence of a high level of near-ridge seismicity and a consistent orientation of T-axes subparallel to the ridge axis (Fig. 6b).

These phenomena have been attributed to relaxation of thermo-elastic stresses in young lithosphere (Bergman et al., 1984; Wiens and Stein, 1984; Bergman and Solomon, 1984; Bratt et al., 1985). Relaxation of thermo-elastic stresses, however, does not explain why the occurrence of tensional events in young lithosphere is found in only a few regions of the world, nor why these events should predominate in the Central Indian Ocean (Wiens and Stein, 1984). Another observation not easily explained by the relaxation of thermo-elastic stresses is the age range of normal faulting events in the Central Indian Ocean (ages up to 35–40 Ma). This age span is far greater than that observed for other areas, where normal faulting events in oceanic lithosphere with ages in excess of 20 Ma are absent (Wiens and Stein, 1984). The majority of the events in oceanic lithosphere with an age less than 40 Ma in the Central Indian Ocean are extensional events, whereas in other oceans compressional mechanisms dominate (Wiens and Stein, 1984) even in young lithosphere (age less than 20 Ma). Furthermore, the level of the seismicity on the Indo-Australian plate side of the Southeast India Ridge seems to be much higher than on the Antarctic plate adjacent to the spreading ridge (Bergman and Solomon, 1984), while tensional events such as found in the Chagos area are not even reported from the adjacent African plate (Wiens and Stein, 1984). As demonstrated by Wiens (1986), the concentration of tensional seismic events in the Indo-Australian plate is not an anomaly due to the shortness of the time period covered by the studies by Bergman and Solomon (1984) and Wiens and Stein (1984).

The results of our model calculations give support to the suggestion of Wiens and Stein (1984) that the near-ridge tensional deformation in the Indo-Australian plate is not solely due to relaxation of thermo-elastic stresses but is primarily the consequence of processes unique to the Indo-Australian plate. Our modelling demonstrates a causal relation between forces acting on the downgoing slab at the Java segment of the Java–Sumatra trench system and the stress state in the area adjacent to the Southeast- and Central India ridges.

The Ninetyeast Ridge and the Bay of Bengal

For this area our modelling shows a concentration of compressive stresses with a magnitude (up to 4–5 kbar) greater than those we have calculated for any other part of the Indo-Australian plate. This applies in particular to the northern segment of the Ninetyeast Ridge area, where the effects of the compressive resistance associated with the Himalayan collision and the subduction of young lithosphere off the northern part of the Sunda arc are focused. Previous suggestions (e.g., Weissel et al., 1980; Stein and Okal, 1978) relate the unusually high level of deformation in the area of the Ninetyeast Ridge and the Bay of Bengal to the Himalayan collision. On the basis of the action of compressive resistive forces alone, however, one would expect a decrease of the magnitude of the stresses with distance from the collision front and a more symmetric distribution of stress and deformation in the oceanic lithosphere with respect to the Indian Peninsula. Our results obtained by inclusion of age-dependent forces in the modelling provide a consistent explanation for the concentration of seismic activity in the Ninetyeast Ridge area, in particular for the occurrence of events of M_s magnitudes greater than 7 along the northern tip (Stein and Okal, 1978).

Stress orientation data from Bergman and Solomon (1985) given in Fig. 7 show a rotation of the observed stress field in the area from N–S oriented compression in the north to a more NW–SE directed compression in the southeastern part of the region. A similar pattern is found in the calculated stress model (see Fig. 7). A noteworthy feature of the stress orientation data is the continuity of observed stress directions across the Ninetyeast Ridge. The presence of the Ninetyeast Ridge does not seem to influence the orientation of the stress field.

Minster and Jordan (1978) have demonstrated that closure of the Africa–India–Antarctica triple junction requires internal deformation of the Indo-Australian 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 Indo-Australian plate along the northern part of the Ninetyeast Ridge. On the basis of a more recent inversion of plate motions (see also Stein and Gordon, 1984), and consideration of intraplate seismicity, Wiens et al. (1985) argue in favour of a diffuse plate boundary located in the equatorial Indian Ocean. The proposed diffuse plate boundary includes the northern part of the Ninetyeast Ridge. It should be noted that, although our stress model is based on the distribution of forces at the boundaries of the *conventionally* defined Indo-Australian plate, significant intraplate deformation is predicted in the areas where plate convergence has been proposed by Minster and Jordan (1978) and Wiens et al. (1985).

Buckling of oceanic lithosphere. Significant brittle deformation by high-angle reverse faulting (J.K. Weissel, pers. commun., 1981) in oceanic crust has been inferred from seismic reflection data from the southern part of the Bay of Bengal (Weissel et al., 1980). Anomalously high heat flow in the area seems to be associated with the inferred high level of intraplate deformation (Geller et al., 1983). Another feature specific to this area is the occurrence of broad, hitherto rather puzzling, basement undulations coinciding with undulations in geoid and free-air anomalies with a spacing of roughly 150 km.

These undulations have been recently confirmed by Soviet marine geophysical work in the area (Neprochnov et al., 1985). Weissel et al. (1980) proposed buckling of the lithosphere as an explanation for the undulation of the basement. The buckling stress, which they inferred from a uniform elastic plate analogy of the mechanical properties of the lithosphere in the Bay of Bengal, was of the order of several tens of kilobars. Using SEASAT altimeter data and a linearized depth-dependent rheology of the lithosphere, McAdoo and Sandwell (1985) showed that stresses of 5–6 kbar are required to induce folding of the oceanic lithosphere in the Bay of Bengal. These values are in rough agreement with the results of our model calculations which indicate a compressional stress of 4–5 kbar for this area.

The Java–Sumatra trench system

The calculated stress field displays significant variations along the strike of the Sunda arc. Compression occurs seaward and parallels to the Sumatra trench segment, consistent with the fault plane solution of event 11 given in Fig. 5. Off Java, where stress orientation data are absent, the calculated stress field shows tension perpendicular to the trench. The transition from a compressive stress field off and parallel to Sumatra to a tensional stress field normal to Java, is the result of the contrast in 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 in that area studied by Ward (1983) provides evidence of a raised neutral surface compatible with a regional compressive stress field.

As demonstrated for the Peru–Chile trench (Wortel and Cloetingh, 1985), lateral variations in the component of the regional stress field perpendicular to the trench greatly influence the style of trench tectonics. Regional tension lowers the neutral plane in the bending plate, and promotes the development of grabens, whereas regional compression results in the opposite. These grabens play a crucial role in the accretionary processes at trench systems (Hilde and Sharman, 1978; Schweller and Kulm, 1978). If the grabens are shallow, the trench sediments are not all carried down into the subduction zone, but accrete on the continental margin. If the grabens are well developed, the trench sediments can be trapped in them and are carried down into the subduction zone, eventually leading to tectonic erosion of the margin.

Figure 8 displays the stress component ($\sigma_\perp$), in the direction perpendicular to the Java–Sumatra trench. As a normal component it acts on a vertical plane parallel to the trench axis.

Strong lateral variations occur in the development of grabens along the Sunda arc (Hilde, 1983), as indicated in Fig. 8a. A comparison of Figs. 8a and 8b demonstrates that the region, south of the Java–Flores segment, where tension is perpendicular to the trench coincides with the area of observed (Hilde, 1983) selective occurrence of well developed grabens. The presence or absence of grabens should be considered as an independent basic condition on which the volume of supplied sediments is to be superimposed, before the net outcome for the accretionary process can be predicted. In addition, variations in the normal component of the convergence rate should be taken into account. Results of such an analysis will be presented elsewhere (Wortel and Cloetingh, 1986).

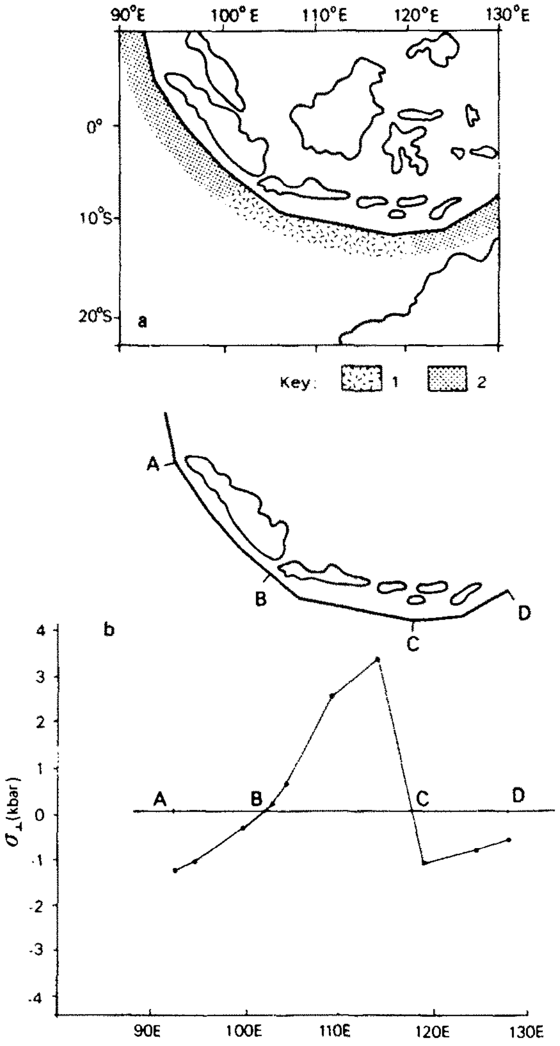


Fig. 8. a. Lateral variation in graben development in the subducting Indo-Australian plate along the Sunda arc. Symbols 1 and 2 denote well developed grabens in subducting plate and areas where grabens are not obvious. (After Hilde, 1983.) b. Lateral variation of the stress component ($\sigma_\perp$) normal to the Java–Sumatra trench. Sign convention: tension positive, compression negative.

Australia and peripheral areas

Evidence from focal mechanism studies indicates that large parts of the Australian continent are in a state of horizontal compression (Denham et al., 1979; Lambeck et al., 1984). On the basis of observational evidence and modelling of gravity and topography, Lambeck et al. (1984) and Stephenson and Lambeck (1985) have suggested a magnitude of the order of 1–2 kbar for the regional stress field. As shown in Fig. 9, 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 southwest Australia to N–S compression in central Australia. In southeast Australia a more complex state of stress has been observed (Lambeck et al., 1984). Our modelling shows that the rotation of the stress field in the Australian continent is mainly the consequence of its geographic position relative to the surrounding trench segments and the variations of the forces acting on the downgoing slab in each. 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.

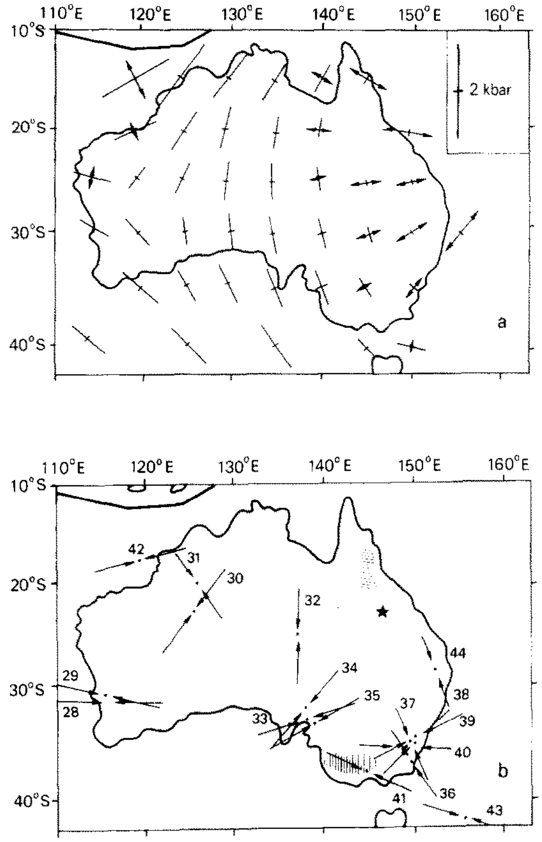


Fig. 9. Regional stress field in the Australian continent and peripheral areas. a. Calculated stress field taken from Fig. 4. b. Stress orientation data from focal mechanism studies. Hatched areas mark the regions with Late Pliocene to present basaltic volcanism in northern Queensland (Griffin and McDougall, 1976) and Victoria (McDougall et al., 1966; McDougall and Gill, 1975). The site of excessive He degassing (Torgersen and Clarke, 1985) is marked by a star.

Eastern Australia. According to our modelling, the occurrence of a tensional component in the stress field in east Australia is induced by a pull exerted on the downgoing slab in the New Hebrides trench and the suction force active on the Tonga–Kermadec plate boundary. The action of net tensional forces along these segments and the presence of a tensional regional stress field off the New Hebrides and off the Tonga–Kermadec trench is consistent with a wide range of geological and geophysical observations in these areas. These are the exceptionally low seismologically observed (Ward, 1983) position of the neutral surface and the superficial structures of the downgoing plate inferred from marine geophysical investigations (Burne et al., 1986), both of which *require* subduction related regional tension off large segments of the New Hebrides trench.

The occurrence of back-arc spreading off Tonga-Kermadec is also consistent with regional tension. The observational evidence for an associated tensional stress field in southeastern Australia, however, is in itself less conclusive. The earthquake evidence for compressive stresses in southeast Australia has been reviewed by Denham et al. (1979; 1981). As noted by Denham et al. (1981), the directions of the *P*-axes, from all the earthquakes for which focal mechanisms have been determined, fail to form a consistent pattern, and it is possible that the faulting associated with the southeast Australian seismic events is dominated by the geometry of pre-existing crustal faults or zones of weakness. In addition, geological observations in eastern Australia are easier to reconcile with a tensional regional stress field. This applies in particular to recent basaltic volcanic activity (late Pliocene—2.7 Ma ago—to present) in northern Queensland (Griffin and McDougall, 1976) and Victoria (McDougall et al., 1966; McDougall and Gill, 1975). Furthermore, the measured continental flux of crustal Helium in the

Great Artesian basin of Queensland is consistent with fracturing of the crust under tensional stresses (Torgersen and Clarke, 1985).

Australian passive margins. Significant variations in the regional stress field occur along the Australian passive margins. This is especially evident along the eastern Australian margin. There the calculated regional stress field is roughly perpendicular to the margin, varying along the margin from NW–SE tension in the north to NE–SW tension and finally to E–W compression in the south. For this reason, the Australian margins offer a specially interesting case for analysing the relationship between variations in *regional* stress fields and those in *local* flexural stress fields induced by sediment loading on the passive margins (Cloetingh et al., 1982; 1983, 1984) and for the study of their effect upon tectonic style and subsidence.

Discussion

The high level of intraplate seismicity in the Indo-Australian plate makes intraplate earthquakes a reliable indicator of the regional stress field (Bergman and Solomon, 1985). Our modelling has shown that the regional stress field in the plate is characterized by an order of magnitude of several kilobars. This is an order of magnitude higher than the regional stress field normally associated with plates, as can be inferred from our modelling of the stress field in the Nazca plate. In Wortel and Cloetingh (1985) we have shown that the style of trench tectonics reflects variations in the regional stress field. Therefore, marine geophysical data from the trench areas constitute a pertinent source of information to be used in stress modelling in convergent plates with a low level of intraplate seismicity. Plates that are not involved in collision or subduction processes are not subject to the influence of slab pull forces.

It has been shown here and in previous work (Wortel and Cloetingh, 1981) that concentration of these forces dominates the regional stress field. In the absence of slab pull forces locally induced stresses can be much more important than the regional stress field. Thus, for passive margins located in the interiors of the American plates stresses induced by sediment loading are an order of magnitude greater than the regional stress field associated with ridge push forces (Cloetingh et al., 1983, 1984).

On these grounds, the Indo-Australian plate provides an especially pertinent case to compare the outcome of lithospheric regional stress modelling with stress indicator data from earthquake focal mechanism data. The broad heterogeneity in lithospheric structure caused by the joint presence of oceanic and continental fragments in the Indo-Australian plate does not seem to influence the stress field drastically. This is apparent from the continuity of the observed stress field across the Ninetyeast Ridge (Bergman and Solomon, 1985). It is further supported by the outcome that modelling that does not take into account differences in lithospheric structure has been able to provide an excellent fit with most of the stress data both from the interior of the plate and from seismological and marine geophysical studies in the trench regions. Additional diffuse plate boundaries in the interior of the Indo-Australian plate, such as recently proposed by Wiens et al. (1985) on *kinematic* grounds, can be easily incorporated into our modelling. This permits independent testing of the presence of such features in the light of *dynamic* observations.

We found that the joint occurrence of high levels of compressional deformation and normal faulting observed in the interior and parallel to the spreading ridges of the plate is not a coincidence. Both features turn out to be closely associated with the unique present-day dynamic situation of the Indo-Australian plate. The relief of thermoelastic stresses at spreading centers (Bergman et al., 1984) cannot by itself explain why normal faulting earthquakes are overrepresented in this particular plate. Our modelling strongly supports a causal relation between forces acting on the downgoing slab at the Java segment of the Java–Sumatra trench system and the state of stress in the area adjacent to the Central- and Southeast India ridges by transmission of stresses over distances of several thousand kilometres. Spatial continuity of stresses and long distance stress propagation away from convergent boundaries are also supported by observations of palaeostress field directions (e.g., Letouzey and Trémolières, 1980; Letouzey, 1985) and present-day stress fields (e.g. Bergman and Solomon, 1985).

Apart from spatial variations, the stress field in the Indo-Australian plate has been subjected to *temporal variations* associated with its time-dependent behaviour at the convergent margins. One example of this is the onset of the Banda arc collision, where a period during which the stress would have been controlled by slab pull associated with subduction of old oceanic lithosphere (Richter and McKenzie, 1978; England and Wortel, 1980) was followed about 5 Ma ago by a phase of net resistance due to the arrival of the buoyant continental lithosphere at the subduction zone (Veevers et al., 1978; Johnston and Bowin, 1981). We also conjecture that the onset of the Himalayan collision (Patriat and Achache, 1984) induced significant changes in the regional stress field in the plate. Less dramatic changes in stress regime of a continuous rather than an abrupt character occur when the age of the lithosphere entering the trench system- and consequently the age-dependent slab pull force (England and Wortel, 1980) and the geometry of the downgoing slab (see Wortel, 1984 for the South American zone) varies with time. The interaction of the temporal fluctuation in the in-plane forces of the lithosphere with the deflections of the lithosphere caused by sediment loading provides a mechanism (Cloetingh et al., 1985) for regional sealevel fluctuations deduced from seismostratigraphic analysis of sedimentary basins by Vail et al. (1977). Specific rapid falls in the Vail et al. (1977) curves can be associated quantitatively with particular plate-tectonic reorganizations of lithospheric stress fields (Cloetingh et al., 1985). The seismostratigraphic record may provide a new source of information on paleo-stress fields to be correlated with results of independent numerical modelling of intraplate stresses.

Conclusions

The high level of the stress field, the dominance of compression and the strong variations in observed stress directions in different areas of the Indo-Australian plate are consequences of its unique dynamic situation.

The calculated stress field elucidates the intraplate tectonics in the Ninetyeast Ridge area, where the effects of compressive resistance associated with Himalayan collision and subduction of young lithosphere off the northern part of the Sunda arc are focused. The calculated lateral variations in the stress component perpendicular to the Java-Sumatra trench explain the observed selective occurrence of well developed grabens seaward off the Java–Flores segment of the trench. Our modelling provides a greater insight into the observed rotation of the regional stress field in the Australian continent. This rotation is the consequence of the geographic position of the continent relative to the surrounding trench segments.

The incorporation of age-dependent forces in our modelling explains the joint occurrence in this single plate of an exceptionally high level of compressive deformation in the interior together with the concentration of a major part of all normal faulting seismic events in young oceanic lithosphere.

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