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Why does near ridge extensional seismicity occur primarily in the Indian Ocean?

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The possibility that thermoelastic stresses due to plate cooling contribute significantly to the stress field and seismicity in young oceanic lithosphere has been a subject of considerable recent interest. This effect is suggested by three key observations: a decrease in seismicity with lithospheric age, the fact that focal mechanisms show extension perpendicular to the spreading direction, and a depth stratification of mechanism types. A difficulty with this idea is that although thermoelastic stresses should be comparable in different regions, the intraplate seismicity seems to occur in local concentrations. In particular, the ridge-parallel extensional seismicity occurs preferentially in the Central Indian Ocean region.

We explore the possibility that much of the data favoring thermoelastic stresses can be interpreted in terms of stresses resulting from individual plate geometry and local boundary effects. In particular, the dramatic concentration of extensional seismicity in the Central Indian Ocean region is consistent with finite element results for the intraplate stress incorporating the effects of the Himalayan collision and the various subduction zones. The ridge parallel extensional stresses show a decrease with age similar to that of the seismicity. As earthquakes in this area provide a major portion of the data for both ridge-parallel extension and depth stratification, these effects may be due more to the regional stress. We thus propose that thermoelastic stresses provide a low level "background" in all plates, but that the dominant effect is that of individual plate geometry and local boundary effects.

1. Introduction

It has been recognized for some time that intraplate stresses [1] and the velocities of plate motion [2–4] provide most of the constraints usable to test and discriminate models of plate driving forces. In the absence of direct stress measurements, the distribution of earthquakes and their focal mechanisms are compared to those predicted by various models [1,5,6].

Such models assume that the oceanic lithosphere is subject to several forces. The density contrasts due to cooling and thickening of the lithosphere give rise to the "ridge push" force [7,8]. The resulting stress depends on the other forces including viscous drag at the base of plates [9] and the forces applied at ridge, transform and trench boundaries. Early models, which treated all forces as constant and concentrated along plate boundaries, showed that the stress due to ridge push is compressive and, for a cooling halfspace model of the lithosphere, increases as the square root of plate age. The observation that most oceanic intraplate earthquakes in older lithosphere have thrust mechanisms implies that the compressive stresses due to ridge push generally dominate the other effects.

More detailed representations of the stress field can be obtained by explicitly incorporating the variation in forces with lithospheric age and hence location within plates and along their boundaries (Wortel and Cloetingh [10,11] and Richardson and Cox [12]). Such results can be compared to the distribution of intraplate seismicity as a function of position and plate age. Several generalizations can be made. Fig. 1A shows that the level of seismicity decreases dramatically with lithospheric age [13,14]. This effect is especially noticeable when corrected for the fact that the maximum depth of earthquakes is controlled by temperature, so that the relevant variable is the volume of lithosphere of a given age above a limiting iso-

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therm. This provides a useful constraint if, as often assumed, the amount of seismicity reflects the magnitude of stresses. The focal mechanisms of the earthquakes also vary with age. Older oceanic lithosphere shows thrust faulting, indicating deviatoric compression, whereas younger lithosphere has both deviatoric compression and extension [14–16]. In particular, young lithosphere in the Indian Ocean shows significant extensional seismicity (Fig. 1B).

Several constraints are available on the nature of the seismicity in young oceanic lithosphere. The focal mechanisms show extension perpendicular to, rather than in, the spreading direction as expected from a strong ridge which produces a distributed extensional zone [17,18]. As the tensional events show ridge-parallel extension, they may be due to thermoelastic stresses [14,15] which have been proposed by Turcotte and Oxburgh [19], Parmentier and Haxby [20], Sandwell [21] and Lister [22]. An observation possibly favoring this effect is an observed stratification of focal mechanism type in young oceanic lithosphere [14,15]. The depths, derived from body wave modeling, are generally accurate to a few kilometers [23]. Normal faulting events seem to occur deeper, and thus at higher temperatures, than thrust and strike slip events (Fig. 2). Bratt et al. [24] have derived a thermoelastic stress model which predicts such a stratification. This model also shows that the thermal stress would decrease with age, as suggested by the rate of seismicity.

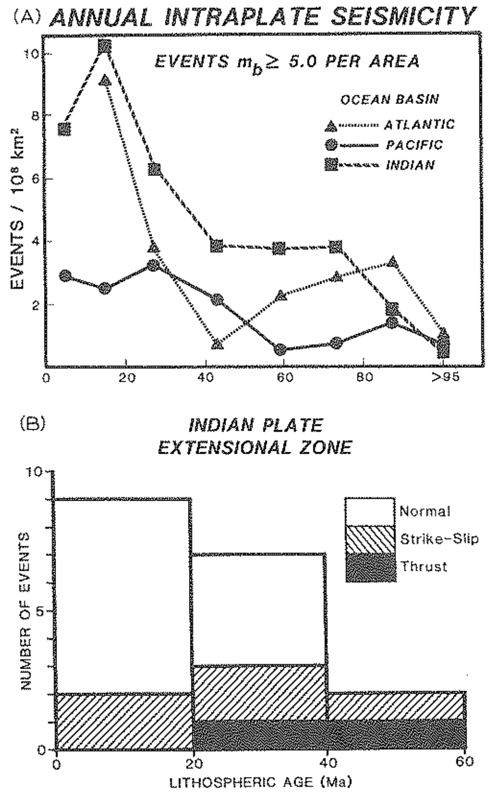

Fig. 1. A. Number of intraplate events per area for the three ocean basins for the years 1964–1981. All three oceans show the highest rates of seismicity in young lithosphere, indicating that this trend is not an artifact of one or two highly seismic zones. Area-age relations are from Sclater et al. [44]. Note the high level of seismicity in young oceanic lithosphere in the Indian Ocean relative to the Pacific and the Atlantic Ocean Basins. B. Types of faulting found in intraplate earthquakes in the Central Indian Ocean, on the Indian plate south of 0° and west of 90°E as a function of lithospheric age. Extensional mechanisms predominate in young lithosphere.

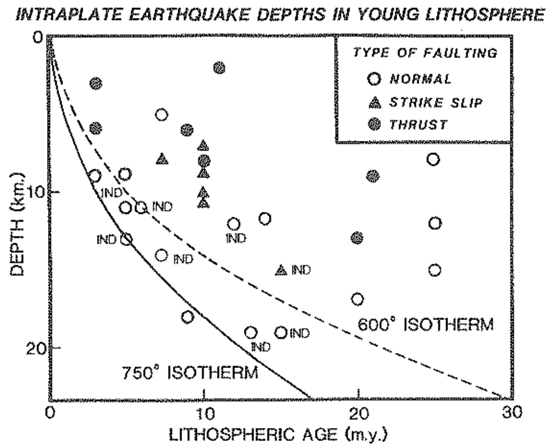

Fig. 2. Depths of intraplate earthquakes in young oceanic lithosphere as a function of lithospheric age. The type of faulting is noted. Isotherms are from the Parsons and Sclater [45] plate cooling model. The depths seem to be limited approximately by the 750°C isotherm [13,14,46]. Normal faulting events seem to be located at greater depths and temperatures than thrust and strike slip events. Note that most deep normal faulting occurs in the Indian plate (events marked with "IND").

Although thermoelastic stress provides an explanation for the decay of seismicity with age, the ridge-parallel extension, and the depth stratification of mechanism type, a possible difficulty with this model is that the earthquakes do not occur uniformly in the ocean basins. They are grouped in several concentrations. In particular, most of the normal fault events occur in an intensely deforming region of the Indian Ocean along the

Central and Southeast Indian Ridges (Fig.3) [14,15,25,26]. The depth stratification (Fig. 2) and mechanism versus age data are thus dominated by this group of events. As thermal stresses should occur everywhere, such concentrations suggests that local effects, like the plate boundary geometry, may be the primary control on intraplate stresses. We examine this possibility using Cloetingh and Wortel's [27,28] model for stresses in the Indian Ocean region.

2. Indian Ocean stress fields

To satisfy the constraint that ridge-parallel extensional seismicity occurs in local concentrations, preferentially in the Indian Ocean region, we assume that stress reflects mechanisms of two types. One is those which should be similar for all plates: "ridge push" force, thermoelastic effects, ridge strength and basal drag. The second, which varies dramatically between and within plates, is the effect of boundary geometry and lithospheric age distribution. The rate and nature of intraplate earthquakes in young lithosphere allow us to assess the relative significance of these effects. Whereas thermoelastic stresses should be comparable in different regions, the existence of unusual concentrations of seismicity within individual plates implies stress mechanisms particular to a plate's geometry and dynamic situation. Our hypothesis is that thermoelastic stresses provide a low level "background" in all plates, and that the dominant effect is that of individual plate geometry and local boundary effects.

To test these ideas, we use the results of stress models for the Indian Ocean region, the type example of intraplate deformation. In addition to the extensional seismicity, strike-slip faulting occurs in the Ninetyeast Ridge area [29,30] and north-south compression occurs between the Ninetyeast and Chagos Ridges, as shown by earthquake mechanisms, marine geophysical [31] and Seasat [32] data.

Since the identification of the anomalous seismicity [33–35] a series of tectonic models have been proposed. Gutenberg and Richter [33] suggested "minor seismic belts" along the northern Ninetyeast Ridge. Sykes [36] proposed a incipient island arc from Sri Lanka to Australia, perhaps due to outward migration of the Indonesian arc. Later studies [29,30], however, show strike-slip faulting along the Ninetyeast Ridge in the area of the proposed subduction. Stein and Okal [29] suggested relative motion between the western portion of the Indian plate, which encounters resistance due to the Himalayan collision, and the eastern portion which subducts normally at the Indonesian arc. This idea was supported by relative plate motion data indicating deformation within the Indian plate [37,38]. Wiens [26] suggested relative motion between northern and southern segments of the Indian plate along a deformation zone extending from Chagos to the Sumatra Trench. The most recent model [39] assumes that a plate boundary separating Indian and Australian plates intersects the Central Indian Ridge near the equator and then runs northward

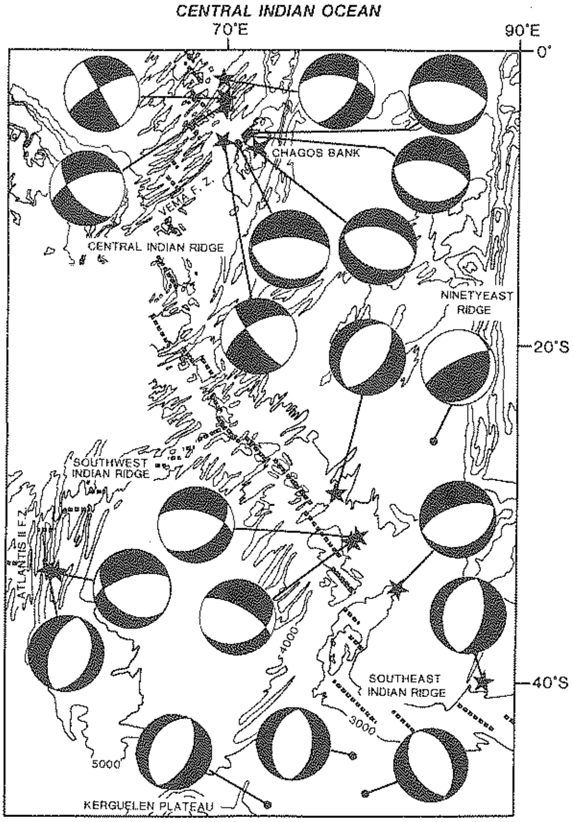

Fig. 3. Near ridge intraplate seismicity of the Central Indian Ocean. Most events indicate a regionally consistent extensional stress field oriented parallel to the ridge axis. Stars are mechanisms from [14]; dots are from earlier studies. Dashed lines denote ridge axes. Bathymetry is shown in 1000 m intervals from Fisher et al. [47].

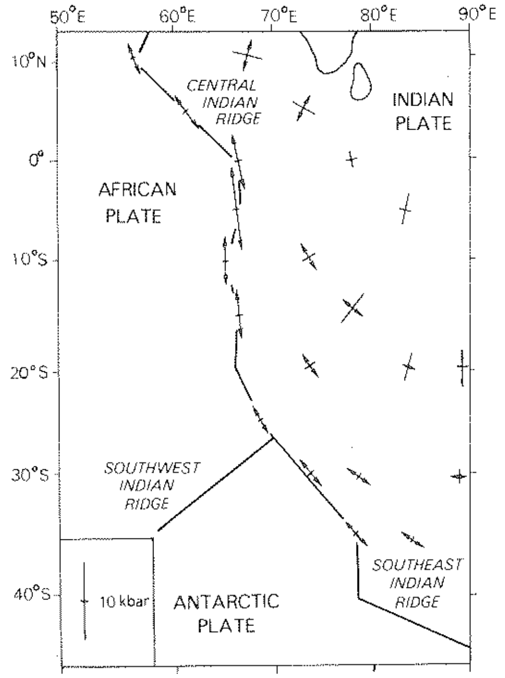

Fig. 4. Stresses in the Central Indian Ocean, modified from [28]. The vertically averaged principal horizontal nonlithostatic stresses are normalized to an elastic plate thickness corresponding to the 600°C isotherm. Symbols (← | →) and (– |–) denote tension and compression, respectively.

along the Ninetyeast Ridge. In this model Arabia, previously considered a separate plate, has no resolvable motion with respect to India. The Euler vector predicts motion with direction and rate consistent with the seismological and geophysical data. In contrast to conventional oceanic plate boundaries, the deformation is distributed over a broad zone. For convenience, we use the traditional term Indian "plate" to describe the entire region, despite the fact that it is better described kinematically as two plates.

Fig. 4 shows the stresses in the Indian Ocean region predicted by Cloetingh and Wortel's [27,28] finite element model which explicitly includes the dependence of "ridge push" and "slab pull" forces on lithospheric age. The stresses, originally calculated for a uniform elastic plate 100 km thick [28], have been rescaled by a plate thickness corresponding to the 600°C isotherm to approximate the increase in mechanical thickness with age. The predicted stresses vary dramatically with position, and show a pattern consistent with the seismological and geophysical observations. In particular, they predict large stress concentrations of the appropriate orientations in the Ninetyeast and Central Indian basin areas. The stress directions predicted by the model, calculated for the conventional Indian plate geometry, are consistent with the observed seismicity in the region interpreted [39] as a diffuse boundary. Moreover, they predict ridge parallel extension in the area along the Southeast Indian Ridge where most of the seismicity in young lithosphere occurs (Fig. 3). Many of these events extend well south of the diffuse boundary zone.

Although any stress model is a non-unique approximation to a complex geological system, the agreement of the model and the available observations is impressive. The model, incorporating the dramatic age variation of the subducting lithosphere and the plate geometry, predicts both unusual deviatoric extension, indicated by the normal faulting, and unusual deviatoric compression, indicated by the strike-slip and thrust earthquakes and major folding. Thus in this model the near-ridge stresses result not purely from effects in young lithosphere but depend on forces applied over the entire plate.

As the stress model includes only the conventionally defined Indian plate, it does not describe the extensional seismicity on the Antarctic plate side of the Southeast Indian Ridge. A full explanation for the zone would require incorporation of the Antarctic plate, where additional extensional events occur, and the African plate, with no near ridge seismicity. Although a stress model for the three plates adequately incorporating the effects of age-dependent driving forces is not presently available, we regard the agreement of the Indian plate model with observations as sufficiently good to be worthy of further investigation.

The magnitudes of the stresses are also of considerable interest. The rescaling for the increase in mechanical thickness with age significantly increases stresses in young lithosphere. Although the actual magnitude of lithospheric stresses are unknown and difficult to constrain [40,41], the predicted values are consistent [28] with those calculated in mechanical models of the folding in the region west of the Ninetyeast Ridge [32,42]. As noted, the high stress regions correlate with the regions of major "intraplate" seismicity. It is thus

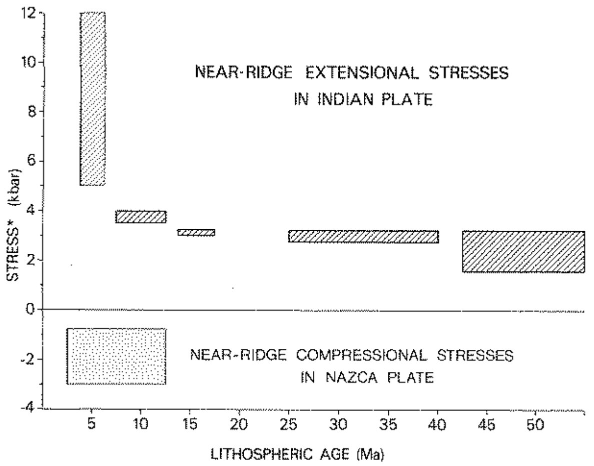

Fig. 5. Calculated vertically averaged horizontally nonlithostatic stresses in young oceanic lithosphere. Ridge parallel extensional stresses in the Central Indian Basin (Cloetingh and Wortel [28]) and ridge parallel compressional stresses in the Nazca plate (Wortel and Cloetingh [43]), calculated for a uniform 100 km thick elastic plate, have been rescaled to reflect plate thickening with age and then averaged for lithosphere in a given age range. The upper panel is thus a spatial average of the values shown in Fig. 4.

possible to evaluate the age dependence of the stress in the region of extensional seismicity. Fig. 5 shows that the average extensional stress decreases dramatically with age. This may well be reflected by the corresponding decrease in the level of seismicity (Fig. 1B). These stresses are of the same order as those predicted by the thermal stress model of Bratt et al. [24], and, in the youngest lithosphere, exceed the expected strength of the material.

It thus appears that a model of the stresses in the Indian plate successfully predicts the unusual concentration of normal faulting events. Moreover, it successfully predicts two of the key observations, ridge parallel extension and decrease in seismicity with age, favoring a thermal stress model. Depth stratification of mechanism type also need not require thermal stresses [14]. Strength envelopes show that the strongest region of the lithosphere occurs at higher temperatures for tensional stresses than for compressive stress. Alternatively, as higher strain rates correspond to greater strength at a given temperature, the normal faulting events may be deeper (Fig. 2) simply because this intensely deforming region has an anomalously high strain rate.

In contrast, models of stresses in young lithosphere in the Nazca plate by Wortel and Cloetingh [11,43] show near-ridge parallel compressional stresses of a much lower magnitude with no comparable change with age. This may be consistent with the absence of the ridge-parallel extensional seismicity there.

3. Discussion

It appears that a large portion of the data interpreted as favoring thermal stresses as a significant factor in young lithosphere intraplate seismicity is equally consistent with the effects of regional stress. This does not, however, require that thermal stresses are not also present. First, although most ridge-parallel extensional events occur in the Indian plate, some occur elsewhere. Second, the decrease of seismicity with lithospheric age is observed for all three major ocean basins (Fig. 1).

We are thus left with the unappealing, but perhaps realistic, view that several effects are operative. Given that most of the ridge-parallel normal faulting in young lithosphere occurs on the Indian plate, it is hard to avoid the conclusion that the regional stress is the primary effect. As some such events occur elsewhere, it seems likely that a global effect, like thermal stress, is also acting.

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