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SEASAT-DERIVED GRAVITY CONSTRAINTS ON STRESS AND DEFORMATION IN THE NORTHEASTERN INDIAN OCEAN

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Abstract. We use SEASAT-derived gravity data to investigate crustal deformation in the NE Indian Ocean. Gravity highs reflecting crustal undulations vary in orientation from E-W in the Central Indian Basin to NE-SW in the Wharton Basin. The undulations vary in trend similarly to the variation of the maximum compression directions predicted by a plate driving force model [Cloetingh and Wortel, 1985], and are essentially restricted to the area of predicted compression for both principal horizontal stresses. This agreement implies that the stress model describes the basic features of the deformation observed in the gravity as well as the seismicity. The gravity data also provide insight into two enigmatic tectonic features. The transition in the morphology of the 90°E Ridge at 10°S from a continuous high to a complex blocky structure appears related to the deformation, since undulations in the Central Indian Basin can be projected eastward to blocks on the Ridge. The morphology, formerly interpreted as a fossil feature, may reflect the recent deformation. The discrepancy between the trends of the southernmost 85°E Ridge and the 90°E Ridge, previously thought to exclude similar hot spot track origins, appears to result from treating a crustal undulation as part of the 85°E Ridge. Earthquakes do not appear to be preferentially located with respect to the peaks and troughs of the undulations.

Introduction

The NE Indian Ocean was, until recently, considered the most active region of oceanic intraplate seismicity [Gutenberg and Richter, 1954; Sykes, 1970; Stein, 1978; Stein and Okal, 1978; Bergman and Solomon, 1985]. North of ~10°S in the Central Indian Basin, sediments and acoustic basement are deformed into long-wavelength undulations associated with large free-air gravity [Weissel et al., 1980; Geller et al., 1983; Haxby, 1987], and geoid anomalies [McAdoo and Sandwell, 1985]. Heat flow is higher than expected for its age [Stein et al., 1988]. The seismicity, high heat flow, and deformation are now interpreted as manifestations of a diffuse plate boundary separating distinct Indian and Australian plates [Wiens et al., 1985] (Figure 1).

SEASAT-derived gravity anomaly data [Haxby, 1987], which provide essentially uniform coverage of the entire area, show the orientation and distribution of folding which could only be identified in a few areas from shipboard data. Figure 2 shows the location of the basement undulations mapped from the SEASAT data, earlier gravity studies, and seismic reflection data. In the Central Indian Basin, undulations trending E-W are best developed from about 3°N-10°S and 80°-85°E (Figure 3), but continue to the west and east. The undulation patterns at 3°S, 83°E are distorted by the Afanasy Nikitin seamounts. Although the northernmost

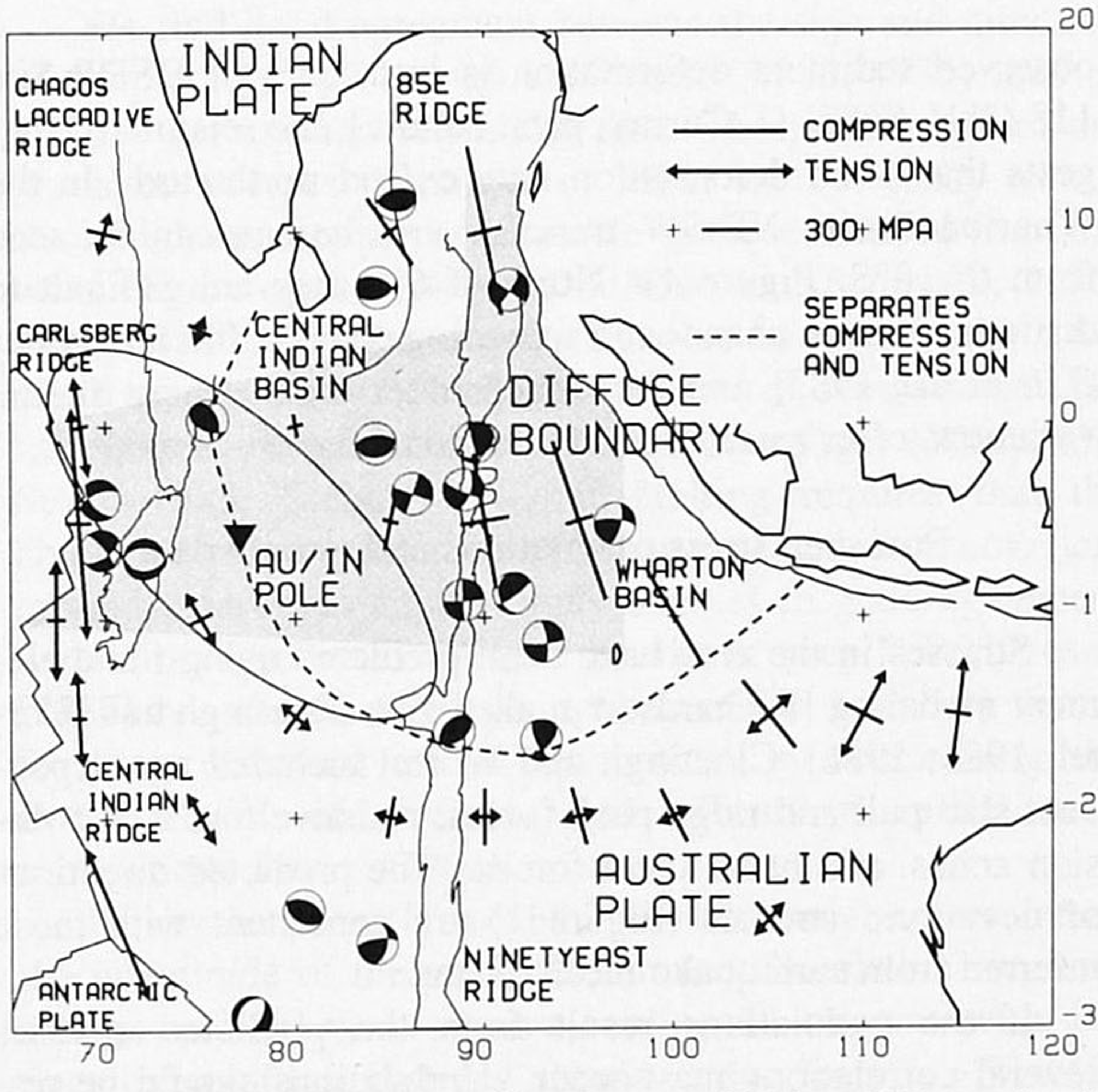

Fig. 1. Plate geometry, predicted stress field and "intraplate" focal mechanisms for the Indian Ocean. Euler pole and 95% confidence ellipse from C. DeMets [pers. comm.]. Principal horizontal deviatoric stresses [Cloetingh and Wortel, 1985] are vertically averaged for an elastic plate thickness corresponding to the 750°C isotherm. Focal mechanisms are from Stein [1978], Wiens and Stein [1983, 1984], Bergman and Solomon [1984, 1985], Wiens [1986], Petroy and Wiens [1989], and Stein and Weissel [1989].

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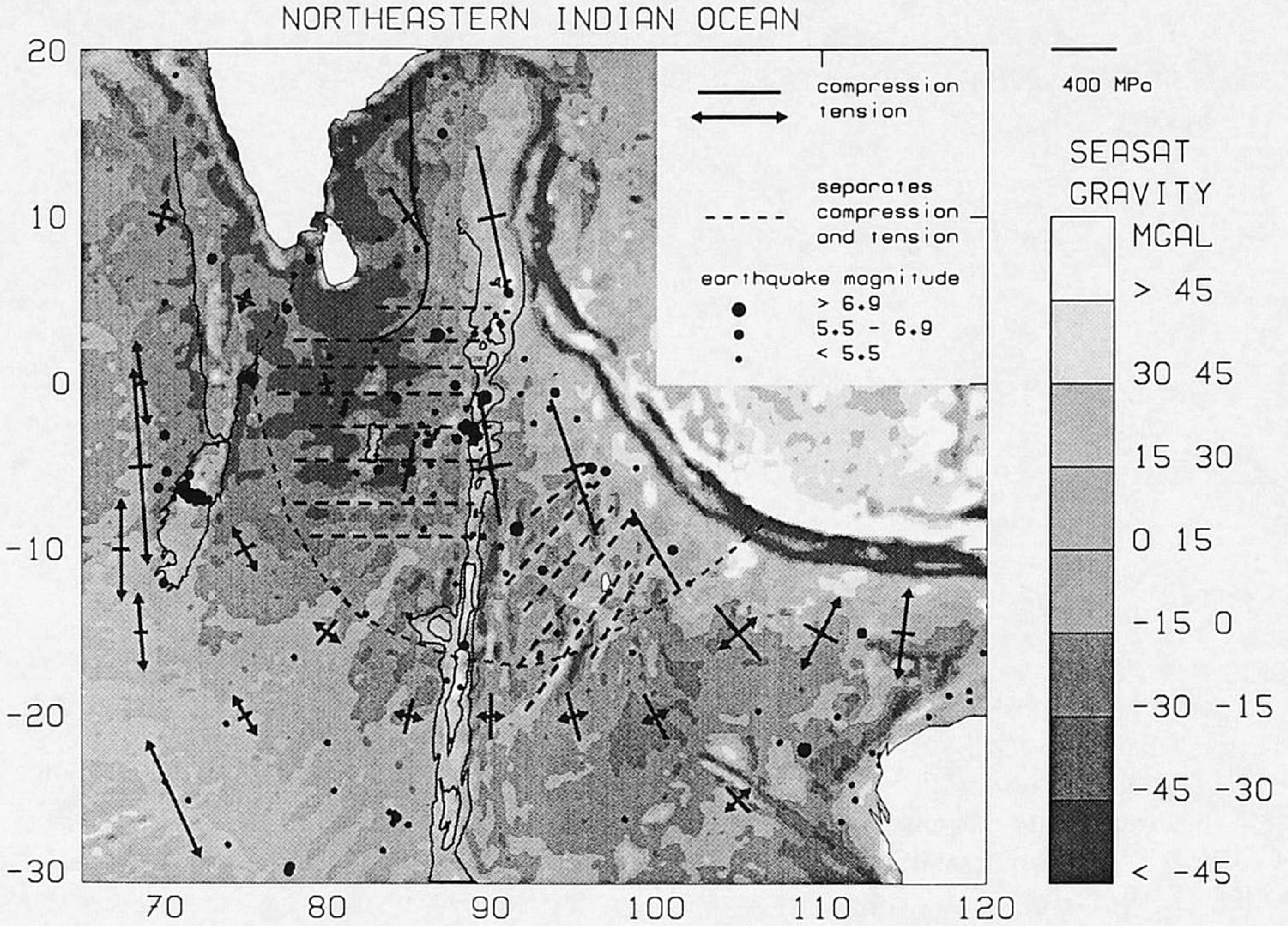

Fig. 2. "Intraplate" earthquakes, gravity anomalies [Haxby, 1987], and predicted stresses (Figure 1). Gravity highs corresponding to the buckled oceanic lithosphere generally trend normal to the predicted maximum compressive stress. The Chagos-Laccadive Ridge is shown by the 3.5 km contour; seamounts and the 90°E Ridge is shown by the 2.5 and 4.0 km contours. Thick solid line shows the trend of the 85°E Ridge. Earthquake relocations are from Wiens [1986] and Petroy and Wiens [1989].

observed sediment deformation is just south of DSDP Site 118 (8°N, 86°E) [J. Curray, pers. comm.], the seismicity suggests that some deformation may extend northward. In the Wharton Basin, NE-SW trending undulations can be seen from 6°-18°S (Figure 4). North of 6°S they are difficult to distinguish from abandoned spreading centers, fracture zones [Liu et al., 1983] and the trench outer high. These spatial variations offer a useful test for regional tectonics models.

Predicted stress orientations and gravity data

Stresses in the area have been predicted using finite element modeling [Richardson et al., 1979; Cloetingh and Wortel, 1985; 1986]. Cloetingh and Wortel included age dependent slab pull and ridge push forces, resistive forces at collision zones, and basal shear forces. The predicted directions of deviatoric stresses (Figure 1) are consistent with those inferred from earthquake mechanisms.

If the undulations result from the predicted stresses several correlations may occur. Undulations should be restricted to the regions of predicted compression and trend normal to the direction of maximum compression. E-W trending folds are expected in the Central Indian Basin from the predicted N-S compression, whereas the predicted NW-SE compression in the Wharton Basin should yield NE-SW trends. The data clearly show this transition across the 90°E Ridge. Furthermore, the undulations extend only slightly south of the predicted transition from compression for both principal horizontal stresses to tension for one of them.

Other morphologic features

The gravity undulations have interesting implications for two prominent features, the 90°E and 85°E Ridges. The morphology of the 90°E Ridge changes at 7-10°S from a smooth continuous ridge to a series of en echelon ENE-WSW trending highs northward [Sclater and Fisher, 1974]. This difference is puzzling since the ridge is thought to be a hot spot track [Morgan, 1972; Pierce, 1978]. Sclater and Fisher suggested that the change in ridge morphology may reflect the separation of Australia and Antarctica. Stein and Okal [1978] noted that the irregular morphology is associated with the region of highest seismicity.

The gravity (Figure 3) shows that highs on the 90°E Ridge are located at about the same latitude and have a spacing similar to undulations in the Central Indian Basin. The depths between the highs and lows on the 90°E Ridge are sometimes ≥1 km, similar to the maximum fold amplitudes in the Central Indian and Wharton Basins. We thus propose that the morphology of the northern 90°E Ridge is a continuation of the undulations and hence reflects the recent deformation which has modified the original smooth morphology, presently preserved to the south. The ENE-WSW trend of the en echelon highs may reflect the predicted variation in the direction of maximum compression across the 90°E Ridge from N-S to NW-SE. Similarly, the smooth morphology occurs where the model does not predict large compressional stresses. Petroy and Wiens [1989] also suggest that the morphology of the northern 90°E Ridge reflects the recent lithospheric buckling. Such models explain the correlation of seismicity, gravity and ridge morphology.

Using shipboard gravity and seismic reflection data, Liu et al. [1982] identified the buried 85°E Ridge extending from ~3°-18°N (Figures 2, 3). Although the ridge approximately parallels the 90°E Ridge north of 5°N, Liu et al. interpreted its trend as diverging to the SW from 3-5°N, and noted that this change precluded a hotspot origin unless the hotspot moved relative to that presumably forming the 90°E Ridge. The SEASAT data (Figure 3) show an undulation high at 3°N, south of Sri Lanka. We propose that this gravity high, previously interpreted as the southern portion of the 85°E Ridge, reflects the recent deformation.

Seismicity

We examined possible relations between the seismicity, gravity, and predicted stresses. Focal mechanisms (Figure 1) are consistent with the displacements predicted by the diffuse plate boundary model [Wiens et al., 1985], since the change from extension to convergence should occur within the boundary zone at the Australia - India Euler pole. It is intriguing that the predicted stress change from compression to tension agrees with the earthquakes and the plate motions.

Given that the undulations and seismicity presumably both reflect the diffuse boundary deformation, it is interesting that the epicenters in the compressional region are not preferentially located with respect to the peaks and troughs of the undulations (Figure 3 and 4). Moreover, the strike-slip earthquakes occur on all parts of the undulations, although the epicenters are often near fracture zones [Stein et al., 1989]. However, since the undulations are not visibly offset, the net horizontal displacement has probably not been significant. In contrast, seismicity within the extensional region near the Chagos-Laccadive Ridge and south and west of the Chagos Bank (6°S, 72°E) appears correlated with the lows in the gravity and bathymetry as well as the location of maximum tensional stresses [Stein et al., 1987]. The coral reef complex has recently undergone very rapid subsidence and drowning [Darwin, 1842].

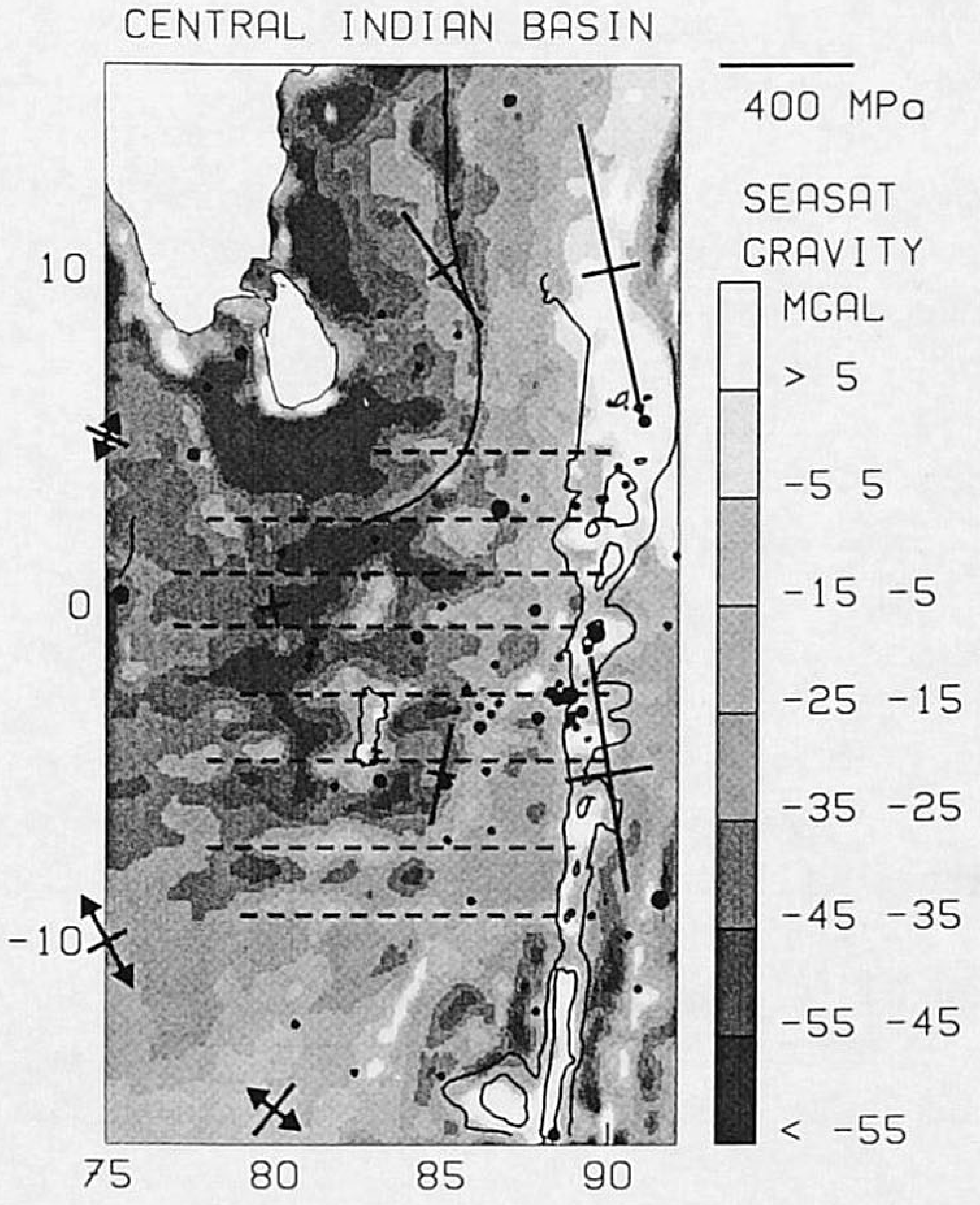

Fig. 3. "Intraplate" earthquakes, gravity, and stresses (Figure 2) for the Central Indian Basin and 90°E Ridge. The highs on the 90°E Ridge appear to be a continuation of the pattern from the west.

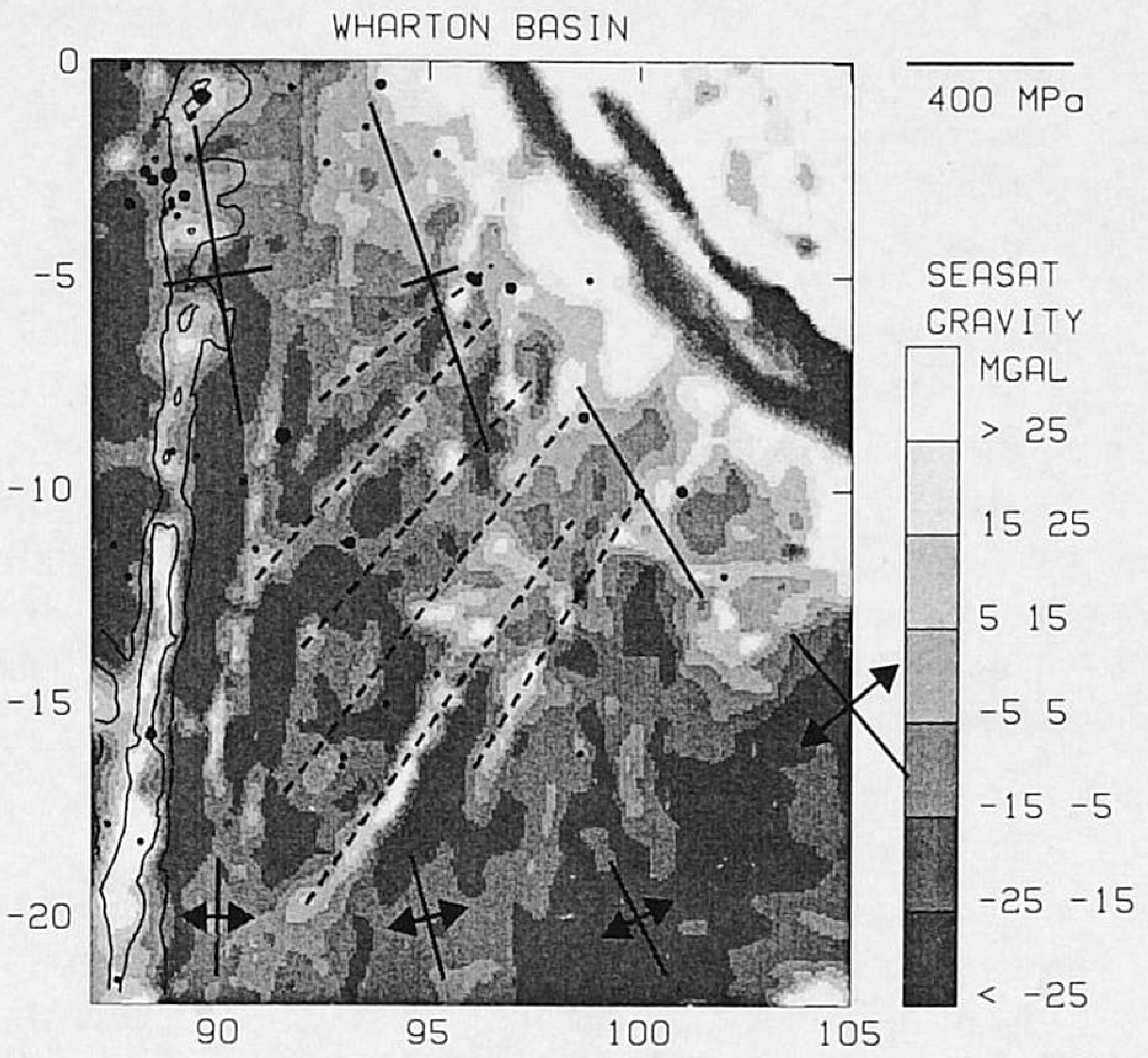

Fig. 4. "Intraplate" earthquakes, gravity, and stresses (Figure 2) for the Wharton Basin.

Discussion

We find good agreement between the sign and direction of the predicted [Cloetingh and Wortel, 1985; 1986] stresses and the gravity and seismicity data. The magnitudes of the predicted stresses (hundreds of MPa) are not easily tested. Such high stresses are comparable to those inferred from the wavelengths of the folding [McAdoo and Sandwell, 1985; Zuber, 1987]. Similar stresses can also be inferred from the depth of seismicity, which often occurs at depths where the lithosphere should have considerable strength [Wiens and Stein, 1983; Stein, 1984]. If faulting requires that the ambient stress equal or exceed that expected on rheological grounds, the focal depths imply stresses in good agreement with those predicted [Wortel et al., in prep.]. Richardson [1987] has shown that assumptions of the boundary forces for the collisional zones are critical in determining the overall level of stresses, and offered a model with significantly lower stresses.

It may be possible to obtain an additional constraint on the magnitude of the predicted stresses. A relative sea level change of ~50 m at passive continental margins with distinct onlap/offlap patterns should occur from a ~50 MPa stress change [Cloetingh et al., 1989]. Thus, apparent sealevel changes along the Indian and northwestern Australian margins should have occurred, given the high predicted stresses. Unfortunately, little information has been published in a format useful for analysis and the Indian sealevel studies are complicated by the Himalayan uplift and fan deposition. Pandey [1986] suggests the east Indian shelf experienced major uplift and regression ~12 Ma. Given that the stress required to produce significant relative sealevel changes at passive margins is an order of magnitude less than that required to buckle the Indian Ocean lithosphere, if the stress slowly increased with time the continental margins might record the stress changes prior to the ~7.5 Ma [Cochran et al., 1988] onset of the deformation.

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