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# A DIFFUSE PLATE BOUNDARY MODEL FOR INDIAN OCEAN TECTONICS

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*Abstract.* Australia and India are conventionally thought to be contained in a single plate divided from an Arabian plate by the Owen Fracture Zone. We propose instead that motion along the nearly aseismic Owen Fracture Zone is negligible and that Arabia and India are contained within a single Indo-Arabian plate, divided from the Australian plate by a diffuse boundary. This boundary, which trends E-W from the Central Indian Ridge near Chagos Bank to the Ninetyeast Ridge, and north along the Ninetyeast Ridge to the Sumatra Trench, is a zone of concentrated seismicity and deformation heretofore characterized as "intraplate". Plate motion inversions and an F-ratio test show that relative motion data along the Carlsberg Ridge are fit significantly better by the new model. The misclosure of the Indian Ocean triple junction is reduced by 40%. The rotation vector of Australia relative to Indo-Arabia is consistent with the seismologically observed ~2 cm/yr of left-lateral strike-slip along the Ninetyeast Ridge, N-S compression in the Central Indian Ocean, and the N-S extension near Chagos. This boundary, possibly initiated in late Miocene time, may be related to the opening of the Gulf of Aden and the uplift of the Himalayas. The convergent segment of this boundary may represent an early stage of convergence preceding the initiation of subduction.

## Introduction

The Indian Ocean's seven large (M > 7.0) "intraplate" earthquakes (Figure 1) include the largest oceanic "intraplate" earthquake known, the 1928 M 7.7 Ninetyeast Ridge event. This level of "intraplate" seismicity is unequaled; the only other magnitude 7 oceanic intraplate earthquakes occur at passive continental margins [Stein et al., 1979] or sites of active volcanism like Hawaii. In striking contrast to the "intraplate" seismicity, the Owen Fracture Zone, traditionally assumed to be the boundary between Arabian and Indian plates, is seismically quiescent [Quittmeyer and Kafka, 1984]. As the two largest earthquakes are magnitude 5.5 and 5.6, the seismic moment of all historical earthquakes along the Owen yields a slip rate less than 0.25 mm/yr, two orders of magnitude less than along the Ninetyeast Ridge. This moment release, anomalously small for a strike-slip boundary, is comparable to that on "inactive" fracture zones [Wiens and Stein, 1984] or intraplate bathymetric features [Stein, 1979].

Should the relatively aseismic Own Fracture Zone be regarded as a plate boundary while the high seismicity of the Central Indian Ocean is treated as "intraplate"? We think not, but development of an alternative model has been hampered by two difficulties. First, it has been unclear how the N-S strike-slip boundary along the Ninetyeast Ridge extended past the point (10°S) where seismicity ceases. Second, the relation between the Chagos and Ninetyeast Ridge concentrations of seismicity has been unclear.

A recent proposal based on the analysis of historic earthquakes [Wiens, 1985] suggests an alternative model in which the Ninetyeast Ridge seismicity is connected to the Central Indian Ridge by an east-west zone (Figure 2) including the Chagos seismicity. We propose here that this boundary separates an Australian plate from a combined Indo-Arabian plate, the Owen Fracture Zone having only negligible motion. This model solves the two problems noted above.

## Relative plate motions

Spreading rates, determined from magnetic anomalies, transform azimuths, and earthquake slip vectors provide an independent test of this new model. Prior analyses of these data have shown several enigmas. Minster and Jordan [1978] noted that Indian Ocean relative motion data were poorly fit, as indicated by non-closure of the Indian Ocean triple junction, suggesting deviations from the rigid plate model used. Moreover, splitting the Indian Plate south of the Ninetyeast Ridge improved the fit and predicted motion along the Ninetyeast consistent with the seismological results. Stein and Gordon [1984] showed that the improvement in fit caused by splitting the Indian Plate was greater than attributable merely to the addition of another plate (and thus three more free parameters) to the model.

How does the new model fit the plate kinematic data? Figure 3 (top) shows the critical experiment using relative motion data from the Gulf of Aden and the Carlsberg and Central Indian Ridges. We treat the region south and west of these spreading centers as a single Somalian (SO) plate, and the region to the north and east, including areas conventionally regarded as portions of the Indian and Arabian plates, as two plates divided by a boundary we seek to locate. This geometry excludes complications due to Nubia-Somalia relative motion [Chase, 1978; Minister and Jordan, 1978; Stein and Gordon, 1984]. We inverted this three plate system with different locations assumed for the boundary between the Australian (AU) and Indo-Arabian (IA) plates. The minimum in squared error occurs for a boundary between 4°N and the equator. (The

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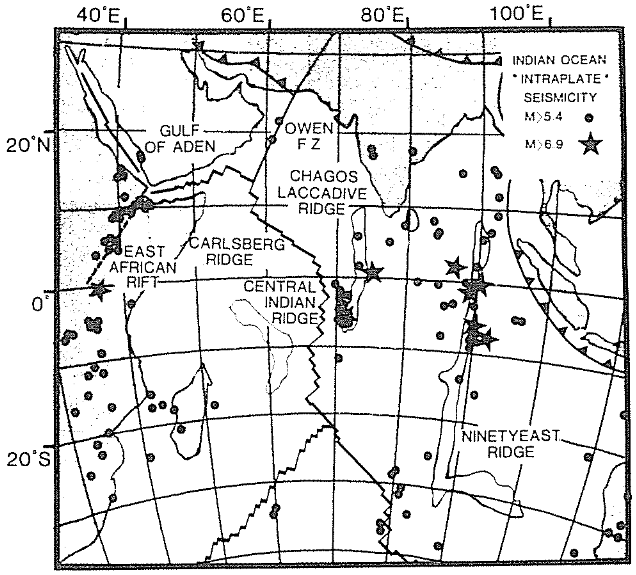

Fig. 1. Earthquakes in the Indian Ocean region (1912-present) located off oceanic spreading centers or conventionally accepted convergent boundaries. Note the intense seismicity between the Ninetyeast and Chagos Ridges and the low level of seismicity along the Owen Fracture Zone.

location cannot be better resolved due to the sparseness of the data.) In contrast, the Owen Fracture Zone yields significantly higher error and is not even a local minimum. The location of the minimum is insensitive to the data inverted; nearly identical locations are obtained from the Minister and Jordan [1978], Chase [1978], or NUVEL-1 [DeMets et al., 1985] data. NUVEL-1, used in Figure 3, contains many data published since 1978.

Figure 3 (bottom) shows why the new model fits better. We predict rates along the Carlsberg Ridge and the azimuth of the Owen Transform (the active segment of the Owen Fracture Zone, traditionally treated as a Somalia-India transform) with Euler vectors derived using data from either the Gulf of Aden or the Central Indian Ridge. The Gulf of Aden curve, the prediction if the Carlsberg Ridge reflects Somalia-Arabian motion, fits much better than the Central Indian Ridge curve, the prediction if the Carlsberg Ridge reflects Somalia-Australian motion. The data are thus better fit if the Carlsberg Ridge bounds the same plate pair as the Gulf of Aden spreading center, rather than the Central Indian Ridge. These problems with the traditional geometry have been noted previously. Laughton et al. [1970] suggested that Carlsberg Ridge and Gulf of Aden data could be fit by a single pole, whereas difficulty in fitting rates on both Carlsberg and Central Indian Ridges with a single pole was noted by Minster and Jordan [1978] and Cochran [1981].

Comparison of magnetic profiles [Matthews, 1966] to synthetics shows that alternative plate motion models can be distinguished (Figure 4). For the profile shown, the rate predicted by an Euler vector fit only to the Gulf of Aden data is 25 mm/yr, whereas 14mm/yr is predicted by an Euler vector fit only to the Central Indian Ridge data. Although the correlation between the data and a model based on a 25mm/yr rate is not excellent, the match to the central anomaly, anomaly 2, and anomaly 2' is reasonable whereas agreement for the slower rate is unacceptably poor.

To test whether the Owen Fracture Zone is a plate boundary in addition to the newly proposed boundary, we applied the F-ratio test of additional boundaries [Stein and Gordon, 1984]. Assuming the SO-AU-IA triple junction is located at 2 °N along the Central Indian Ridge, the value of F for an additional plate boundary along the Owen was well below the threshold for a significant improvement. To construct Figure 3, we varied one parameter, the position of a triple junction. Assuming this represents one degree of freedom, an F test shows that the improvement of the 2 °N triple junction over the Owen triple junction is significant at better than the 99.9% confidence level.

## Discussion

Although very slow motion along the Owen Fracture Zone, a past plate boundary, cannot be excluded, current motion is not required or even suggested by the data. Both seismic and plate kinematic data are consistent with a now-joined Indo-Arabian plate moving relative to a distinct Australian plate. For a boundary at 2 °N, inversion of the global NUVEL-1 dataset yields an AU-IA pole at 1.5 °S, 69.6 °E with a rotation rate of 0.48 °/my. Figure 2 shows the predicted motion: strike-slip along the Ninetyeast Ridge with sense and rate (1.9 cm/yr) of motion consistent with the seismic results [Stein and Okal, 1978] and compression (~1 cm/yr) between the Ninetyeast and Chagos Ridges. Some pole locations within the error ellipse predict extension near Chagos Ridge, in accord with the earthquake mechanisms. The agreement in the Chagos area must be interpreted with caution as different poles within the confidence ellipse predict differing senses of motion.

This model explains both the distribution and mechanisms of the "intraplate" seismicity and provides a better fit to the

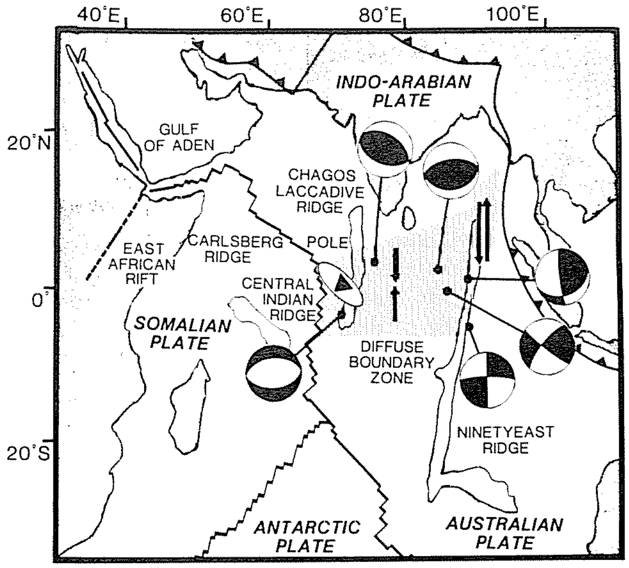

Fig. 2. Schematic of the proposed plate geometry. A diffuse boundary separates Indo-Arabian and Australian plates. Predicted relative motions in the boundary area are consistent with the focal mechanism data. The mechanisms shown are from Stein and Okal [1981], Wiens and Stein [1983; 1984], and Wiens [1985].

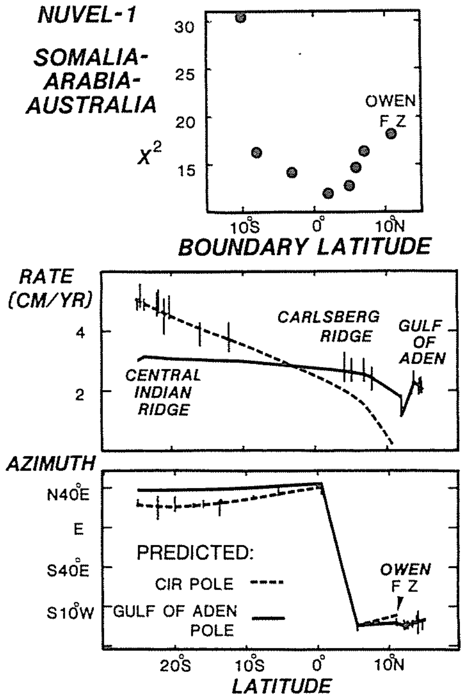

Fig. 3. Plate kinematic test of the proposed boundary geometry. (Top) Misfit to relative motion data as a function of the assumed location of the boundary between Indo-Arabian and Australian plates. The minimum misfit occurs for a boundary between 4 °N and the equator. (Bottom) Rate and azimuth data along the boundary separating Somalia from plates to the east. The Carlsberg Ridge rates and Owen Transform azimuth are better fit by the predictions of a pole from Gulf of Aden data (solid line) than those for a pole from Central Indian Ridge data (dashed line).

relative motion data. The new model, when incorporated into a global plate motion model [DeMets et al., 1985] improves the fit to data along the SE Indian Ridge, which were poorly fit by previous models [Minster and Jordan, 1978]. For the Minster and Jordan [1978] dataset, the magnitude of the misclosure vector for the three plate (Australia-Antarctica-Somalia) system about the Indian Ocean triple junction is reduced by 40%. Neverthless, significant non-closure remains. We thus regard our model not as a panacea for all problems of Indian Ocean plate kinematics, but as the simplest description of motion in terms of idealized internally rigid plates, where one boundary is diffuse, not discrete.

Diffuse plate boundaries have been proposed for other regions such as the Basin and Range, the North America-South America boundary, and the Azores-Gibraltar boundary. As the diffuse IA-AU plate boundary is difficult to define precisely, the geometry shown in Figure 2 is deliberately schematic. The plate motion data test possible intersections of the boundary with the Central Indian Ridge, but provide no information for locating the boundary elsewhere. The seismicity zone just east of the triple junction is ∼800 km wide, apparently extending from the equator to ∼7 °S. The boundary is broader and more diffuse in the Central Indian Ocean; though large earthquakes in the Ninetyeast region are concentrated on the Ridge, a few left-lateral strike-slip earthquakes occur to the east, suggesting a possible shear zone. It is unclear whether a zone of ridge-parallel extension near the SE Indian Ridge [Bergman et al., 1984; Wiens and Stein, 1984; Wiens, 1985] is related to the boundary.

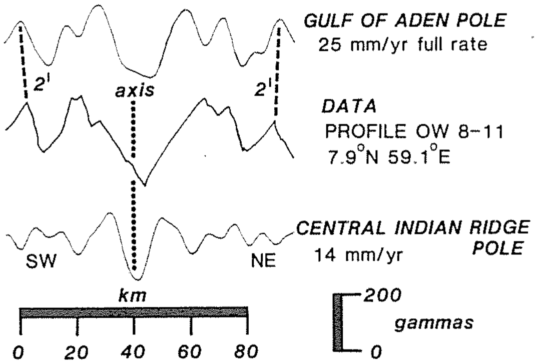

Fig. 4. Carlsberg Ridge magnetic anomalies. Synthetic anomalies for the 25 mm/yr full rate (11 mm/yr spreading SW, 14 NE) predicted by the Euler vector for the Gulf of Aden fit the observed data better than the slower rate predicted from the Central Indian Ridge data. The magnetized body was modeled as 500 m thick, magnetization of 0.007 emu/cm$^3$, 2 km wide polarity transition filter, ambient inclination −2°, declination −3°, and remanent inclination 15° and declination 0°.

The diffuse nature of the boundary may result from the slow relative velocity, its location in old lithosphere, and its relatively recent (late Miocene) development, as indicated by sedimentological data [Weissel et al., 1980]. Present convergence seems accommodated by diffuse deformation, making this the only convergent boundary in the world lacking a collisional mountain belt, morphologic trench, or deep seismicity. Estimation of the total convergence requires assumptions on the deformation history; present rates over 5 Ma predict approximately 50 km shortening. If convergence continues for a long time or the rate increases, subduction may begin. Thus the current deformation may represent the pre-subduction phase of an evolving convergent boundary.

This model has interesting implications for the development of the Indian Ocean. Although the exact timing and sequence are unknown, a number of important tectonic events occur ∼5-10 Ma. Deformation in the Central Indian Basin began in the late Miocene whereas seafloor spreading began in the Gulf of Aden 10 Ma [Stein and Cochran, 1985] and propagated west of 45 °E 4-5 Ma. Thus, the development of the IA-AU boundary may be part of the process of regional plate boundary reorganization, contemporaneous with the separation of Arabia from Somalia and the cessation of motion on the Owen F.Z. It is also tempting to relate formation of the boundary to the late Miocene Himalaya uplift.

Understanding of this complex tectonic environment will improve as additional seismological and plate motion data accumulate. Stress models may provide further insight into the mechanics of the boundary. It is encouraging that recent studies [Cloetingh and Wortel, 1985] yield stresses consistent with the seismicity and our plate motion model.

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