

Direct evidence of active deformation in the eastern Indian oceanic plate

Christine Deplus CNRS/Institut de Physique du Globe de Paris, Case 89, 4 Place Jussieu, 75252 Paris Cedex 05, France
 Michel Diamant } Institut de Physique du Globe de Paris, Case 89, 4 Place Jussieu, 75252 Paris Cedex 05, France
 H el ene H ebert }
 Guillaume Bertrand  cole Normale Sup erieure, 24 rue Lhomond, 75005 Paris, France
 St ephane Dominguez Laboratoire de G eophysique et Tectonique, Universit e de Montpellier II, Case 060, 4 place E. Bataillon, 34095 Montpellier Cedex, France
 Jacques Dubois Institut de Physique du Globe de Paris, Case 89, 4 Place Jussieu, 75252 Paris Cedex 05, France
 Jacques Malod CNRS/Universit e de Bretagne Occidentale, 6 av. LeGorgeu, B.P. 452, 29275 Brest Cedex, France
 Philippe Patriat CNRS/Institut de Physique du Globe de Paris, Case 89, 4 Place Jussieu, 75252 Paris Cedex 05, France
 Bernard Pontoise ORSTOM, UR14-Laboratoire de G eodynamique sous-marine, B.P. 48, 06230 Villefranche-sur-Mer, France
 Jean-Jacques Sibilla Institut de Physique du Globe de Paris, Case 89, 4 Place Jussieu, 75252 Paris Cedex 05, France

ABSTRACT

Conventional plate tectonics theory postulates that plates only deform on their boundaries. To the contrary, there is ample evidence of intraplate deformation in the equatorial Indian Ocean, west of the Ninetyeast aseismic ridge. Prior to this study, no direct evidence of deformation east of the Ninetyeast Ridge was available. We present the results of a multipurpose geophysical cruise showing that intraplate deformation also occurs in this area. Long, at least 1000 km, left-lateral north-south strike-slip faults are active and reactivate fossil fracture zones. This style of deformation is strikingly different from the east-west folds and reverse faults that affect the region west of the Ninetyeast Ridge. Contrasting processes of convergence at the northern plate boundaries can account for the two styles of deformation. West of the Ninetyeast Ridge there is a continent-continent collision, and east of the ridge oceanic lithosphere subducts along the Sumatra trench. The Ninetyeast aseismic ridge therefore appears to be a mechanical border separating two distinct deformed areas.

INTRODUCTION

The equatorial Indian Ocean is a well-known place of intraplate deformation and the deformed area has been interpreted as a diffuse plate boundary between India and Australia (Wiens et al., 1985; Gordon et al., 1990; DeMets et al., 1994). The deformation was predicted from the high level of intraplate seismicity (Stein and Okal, 1978; Bergman and Solomon, 1985; Petroy and Wiens, 1989; Tinnon et al., 1995), stress modeling (Cloetingh and Wortel, 1986), and analysis of satellite-derived gravity data (McAdoo and Sandwell, 1985; Stein et al., 1989). West of the Ninetyeast Ridge, single (Weissel et al., 1980) and multichannel (Bull and Scrutton, 1990; Chamot-Rooke et al., 1993) seismic data have shown that deformation is characterized by folding and active lithospheric reverse faults oriented roughly east-west. East of the Ninetyeast Ridge, i.e., in the Wharton Basin, seismic activity (Petroy and Wiens, 1989; Tinnon et al., 1995) and northeast-southwest satellite-derived gravity anomalies (Stein et al., 1989; Sandwell, 1995) also indicated important deformation, although no direct observation was available. In December 1995, we carried out a marine geophysical survey in the Wharton Basin (Fig. 1). Our results confirm that the oceanic lithosphere

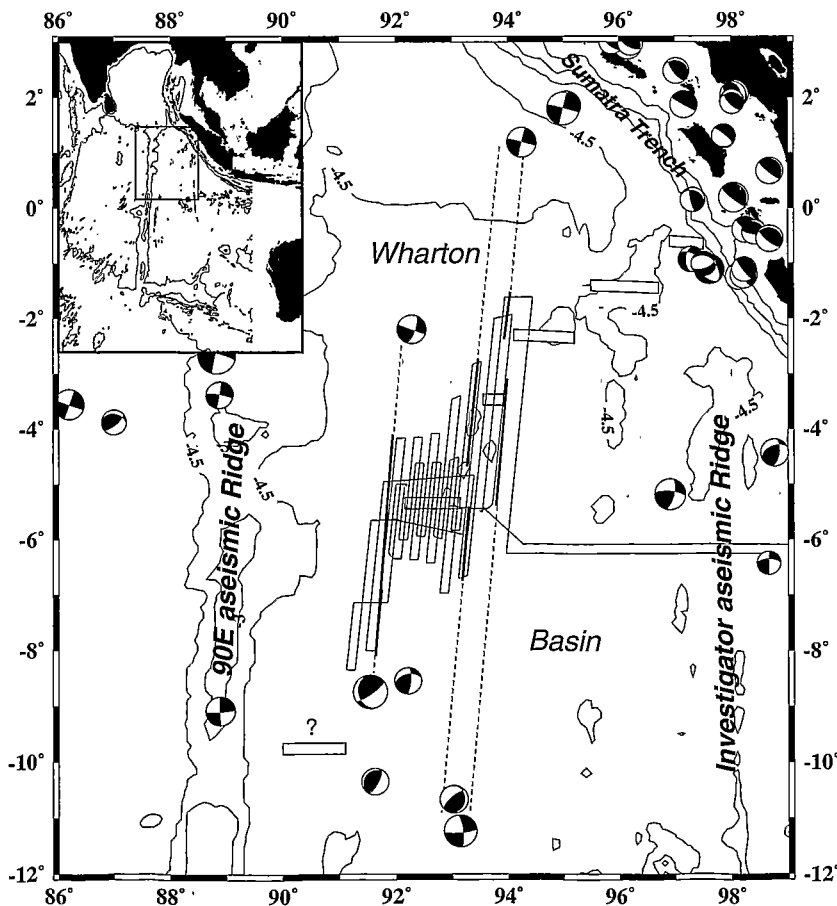


Figure 1. Simplified bathymetric map of Wharton Basin. Contours are in kilometers. Major bathymetric features are Ninetyeast and Investigator aseismic ridges, and Wharton fossil spreading center. Locations of east-west fossil spreading segments (shaded rectangles) are deduced from identification of magnetic anomalies, except for southern one, the position of which is unknown. Thin lines show routes of Samudra cruise. Strike-slip faults identified during this cruise are shown in bold lines. Published focal mechanisms are also reported. Note good agreement between location and mechanism of some earthquakes with prolongations (dashed lines) of observed strike-slip faults. Some earthquakes also indicate that northwest-southeast compression should occur south of our surveyed area.

in this part of the Indian Ocean is actively deforming in a style that contrasts drastically with that of the lithosphere west of the Ninetyeast Ridge. We present and discuss these results here.

RESULTS FROM THE SAMUDRA CRUISE

The lithosphere underlying the Wharton Basin is between 45 and 85 m.y. old. It formed at the Wharton Ridge, a roughly east-west mid-oceanic ridge on which accretion stopped ca. 45 Ma (Liu et al., 1983; Patriat and Ségoufin, 1988; Royer and Sandwell, 1989), leaving a fossil axis left-laterally offset by fossil transform faults (Fig. 1). Therefore, the bathymetric structures in the Wharton Basin are east-west features coinciding with the segments of the extinct ridge and north-south features linked to the old fracture zones. However, except for the most prominent ones, these topographic features are generally buried under the sedimentary cover of the Nicobar fan. To the north, the lithosphere subducts beneath the south-east Asian plate along the Sumatra trench (Fig. 1).

During the Samudra cruise (November 18–December 14, 1995) onboard the French R/V *L'Atalante*, we gathered multibeam bathymetry, sea-floor imagery, 3.5 kHz, gravity, magnetic, and six-channel seismic reflection profiling data in order to investigate the Wharton fossil spreading ridge and possible intraplate deformation. We surveyed two segments of the Wharton fossil ridge axis and associated transforms (Fig. 1). No evidence of compression comparable to the one observed in the Central Indian Basin (Weissel et al., 1980; Bull and Scrutton, 1990; Chamot-Rooke et al., 1993) has been found in the surveyed area, but close to the three surveyed fracture zones, multibeam bathymetry and imagery revealed active deformation (Fig. 2). At about 91°50'E, we followed for about 500 km the clearly expressed linear trace of an active N5°E fault that affects the sedimentary cover. Seismic and 3.5 kHz profiles across the fault confirm that it is currently active because recent sediments are affected (Fig. 3). Along the 500 km, the multibeam bathymetry shows that the fault is underlined by en-echelon compressive and extensive relays. In addition, seismic profiles crossing the fault exhibit characteristic features of either extension, e.g., normal faults, or of compression. Such features are common along strike-slip faults. The shape of the relays (Fig. 2, box b) indicates a present-day left-lateral movement. Close to the two other fracture zones, about 93°20' and 94°E, similar N5°E features were evidenced in the sedimentary cover (Fig. 2). In both cases, they consist of two linear segments slightly offset through an en-echelon structure. We interpreted these structures as tensile cracks (Fig. 2, box a) that also indicate a present left-lateral movement along the N5°E features. These en-echelon structures are located along the fossil transform part of the Wharton ridge fracture zones. Such location can be related to the width and complexity of most transform

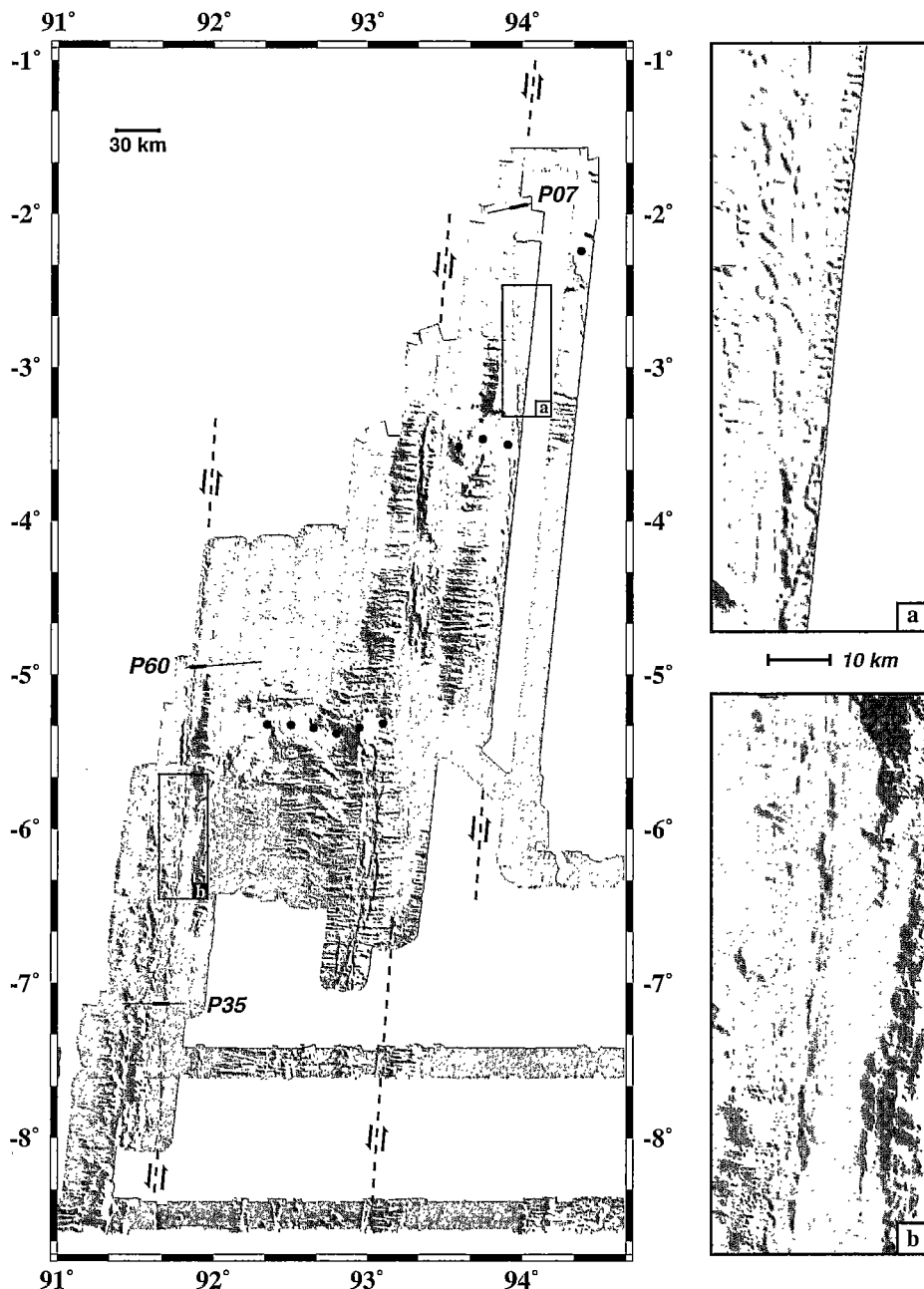


Figure 2. Detailed multibeam bathymetry of area surveyed during Samudra cruise with N60° illumination. Data along two southern east-west profiles were gathered during two previous transits of R/V *L'Atalante* in Indian Ocean. Black dots indicate location of fossil axis deduced from identification of magnetic anomalies. Reliefs associated with fossil ridge exhibit well-pronounced east-west fabric parallel to direction of fossil axis. Linear N5°E features affect sedimentary cover. We interpret them as active left-lateral strike-slip fault zones (see text). Westernmost fault zone is underlined by en echelon compressive and extensive relays (see details in enlarged box b); e.g., small pull-apart graben structures are clearly visible. Shape of relays as well as tensile cracks (box a) on eastern faults imply present-day left-lateral movement. Thick lines indicate location of seismic data shown in Figure 3.

zones on active spreading centers (Searle, 1986; Sempéré and McDonald, 1987).

Our data reveal three active left-lateral strike-slip faults extending across the surveyed area. Published intraplate earthquake locations (Dziewonski et al., 1981, 1996; Timmon et al., 1995) make it possible to infer the length of these faults. Figure 1 shows that some of these earthquakes are located

close to the prolongations of the surveyed faults and exhibit left-lateral strike-slip mechanisms. Because these events are located using data of the world-wide networks, i.e., with only a limited accuracy, we can infer that these events are related to the strike-slip faults we surveyed. These faults are thus major active features of the oceanic lithosphere and extend at least 1000 km.

DISCUSSION AND CONCLUSION

Our data confirm that active intraplate deformation also occurs east of the Ninetyeast Ridge. However, its pattern strongly differs from the deformation west of the Ninetyeast Ridge. In both locations, the oceanic lithosphere has the same preexisting fabric. However, whereas deformation is expressed in the western part by reverse faults reactivating preexisting faults that formed at the spreading center (Bull and Scrutton, 1990; Van Orman et al., 1995), strike-slip faults reactivate old transform faults in the eastern part. The Ninetyeast aseismic ridge is thus a mechanical border separating two distinct styles of deformation. What causes these two distinct deformation patterns? In both areas, the deformation has to be linked with the stress regime inherited from the India-Asia collision. North of the western part, the plate boundary is a continent-continent collision, and north of the eastern part the oceanic plate is subducting beneath a continent, along the Sumatra trench. The subduction along the Sumatra trench is oblique and the eastward decrease in obliquity provides a gradual transition from collision to the west to free border to the east, at the Java trench where the subduction is frontal. This transition in boundary conditions yields to a rotation of the direction of the main compressive stress from north-south in the Central Indian Basin to northwest-southeast in the Wharton Basin (Cloetingh and Wortel, 1986). Such direction for the main compressive stress is in agreement with left-lateral strike-slip motion along north-south features in the Wharton Basin. This style of deformation is also related to the nature of the plate boundary at the Sumatra trench, north of the Wharton Basin. We propose that the lithosphere of the Wharton Basin is cut in north-south slivers because it is progressively more easily subducted eastward. This is another consequence of an oblique subduction: Increase in convergence obliquity along the Sumatra trench was previously invoked for the deformation of the fore-arc area (Diament et al., 1992; McCaffrey, 1992); we propose here that it may also deform the oceanic plate.

Furthermore, this large deformed area has to be included in the diffuse plate boundary between Australia and India. A recent kinematic study (Royer and Gordon, 1997) proposes a three-plate model for the former India-Australia tectonic plate: The new pole of rotation between Australia and India given in this study is in good agreement with left-lateral strike-slip faulting along north-south features in the Wharton Basin.

Another question deals with the termination of the strike-slip faults evidenced in our survey area. According to the published focal mechanisms, they must connect to the trench to the north, but it is unlikely that they reach the southern plate boundary, i.e., the southeast Indian ridge. Moreover, focal mechanisms (Fig. 1) and clear southwest-northeast gravity undulations (Stein

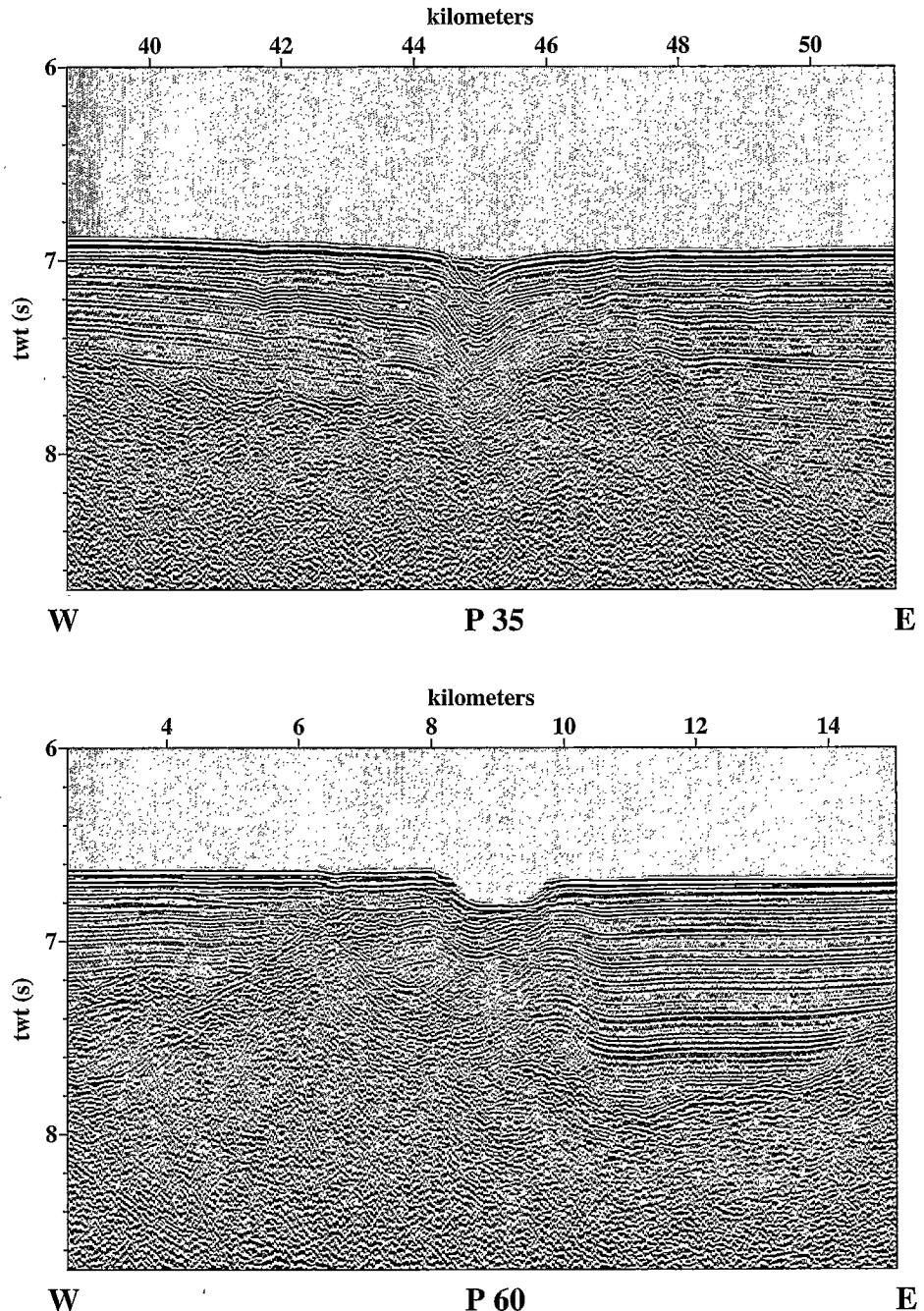


Figure 3. Three seismic profiles crossing active faults. See Figure 2 for their locations. Seismic data were processed with Seismic Unix (Cohen and Stockwell, 1996). Data were stacked and migrated with water velocity. Profiles 35 and 60 intersect westernmost fault and profile 07 intersects easternmost one. Location of fault deduced from multibeam bathymetry is between km 44 and 46 for profile 35, km 8 and 10 for profile 60, and km -8 and -6 for profile 07. All profiles show that sediments are clearly affected. Deformation in basement cannot be detected because of limited penetration of the six-channel seismic reflection technique used here; twf is two-way travel time.

et al., 1989; Sandwell and Smith, 1997) suggest compressive deformation south of the area we surveyed during the Samudra cruise. In this case, the vanishing of the movement along N5°E strike-slip faults in this compressive area should require a decreasing amount of compression toward the east. Further detailed surveys are necessary to test these hypotheses.

To conclude, we provide here a direct evidence of active strike-slip faulting in an intraplate oceanic domain, thereby showing that oceanic plates may undergo a long and continuous deformation process. We have documented a new type of slow, strike-slip, intraplate deformation that reoccupies prior transform/fracture zone shear complexes within a long-dead spreading center.

kilometers

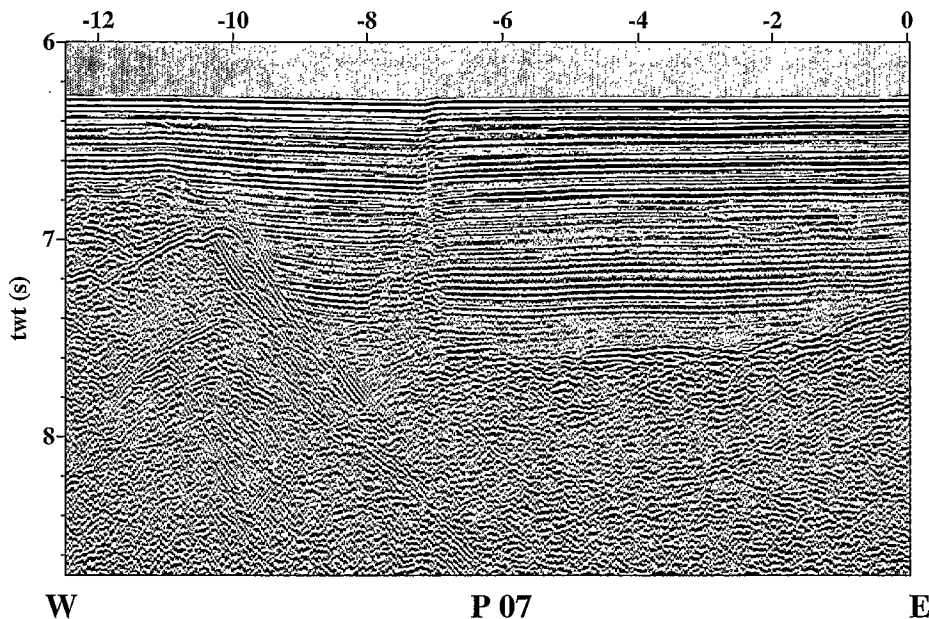


Figure 3. (continued)

ACKNOWLEDGMENTS

We thank the captain, officers, and crew of the N/O *L'Atalante* for their support at sea; the staff of the French Embassy in Indonesia and our Indonesian colleagues for help in the preparation of the Samudra cruise; and J.-C. Komorowski for his comments on the manuscript. We benefited also from useful comments of N. Sleep and an anonymous reviewer. Figures were prepared using the G.M.T. software developed by P. Wessel and W. Smith. This work was supported by CNRS-INSU, Géosciences Marines program. Contribution IPGP no. 1500.

REFERENCES CITED

- Bergman, E. A., and Solomon, S. C., 1985, Earthquake source mechanisms from body-waveform inversion and intraplate tectonics in the northern Indian Ocean: *Physics of the Earth and Planetary Interiors*, v. 40, p. 1–23.
- Bull, J. M., and Scrutton, R. A., 1990, Fault reactivation in the central Indian Ocean and the rheology of oceanic lithosphere: *Nature*, v. 344, p. 855–858.
- Chamot-Rooke, N., Jestin, F., de Voogd, B., and Phèdre Working Group, 1993, Intraplate shortening in the central Indian Ocean determined from a 2100-km-long north-south deep seismic reflection profile: *Geology*, v. 21, p. 1043–1046.
- Cloetingh, S., and Wortel, R., 1986, Stress in the Indo-Australian plate: *Tectonophysics*, v. 132, p. 49–67.
- Cohen, J. K., and Stockwell, J. J. W., 1996, CWP/SU: Seismic Unix release 28: A free package for seismic research and processing: Golden, Colorado School of Mines, Center for Wave Phenomena, 39 p.

- DeMets, C., Gordon, R. G., and Vogt, P., 1994, Location of the Africa-Australia-India triple junction and motion between the Australian and Indian plates: Results from an aeromagnetic investigation of the Central Indian and Carlsberg ridges: *Geophysical Journal International*, v. 119, p. 893–930.
- Diament, M., Harjono, H., Karta, K., Deplus, C., Dahrin, D., Zen, M. T., Jr., Gérard, M., Lassal, O., Martin, A., and Malod, J., 1992, The Mentawai fault zone off Sumatra: A new key for the geodynamics of Western Indonesia: *Geology*, v. 20, p. 259–262.
- Dziewonski, A. M., Chou, T.-A., and Woodhouse, J. H., 1981, Determination of earthquake source parameters from waveform data for studies of global and regional seismicity: *Journal of Geophysical Research*, v. 86, p. 2825–2852.
- Dziewonski, A. M., Ekström, G., and Salganik, M. P., 1996, Centroid-moment tensor solution for April–June 95: *Physics of the Earth and Planetary Interiors*, v. 96, p. 1–13.
- Gordon, R. G., DeMets, C., and Argus, D. F., 1990, Kinematic constraints on distributed lithospheric deformation in the equatorial Indian Ocean from present motion between the Australian and Indian plates: *Tectonics*, v. 9, p. 409–422.
- Liu, C., Curray, J. R., and McDonald, J. M., 1983, New constraints on the tectonic evolution of the eastern Indian Ocean: *Earth and Planetary Science Letters*, v. 65, p. 331–342.
- McAdoo, D. C., and Sandwell, D. T., 1985, Folding of oceanic lithosphere: *Journal of Geophysical Research*, v. 90, p. 8563–8569.

- McCaffrey, R., 1992, Oblique plate convergence, slip vectors, and forearc deformation: *Journal of Geophysical Research*, v. 97, p. 8905–8915.
- Patriat, P., and Ségoufin, J., 1988, Reconstruction of the central Indian Ocean: *Tectonophysics*, v. 155, p. 211–234.
- Petroy, D. E., and Wiens, D. A., 1989, Historical seismicity and implications for diffuse plate convergence in the northeast Indian Ocean: *Journal of Geophysical Research*, v. 94, p. 12301–12319.
- Royer, J.-Y., and Gordon, R. G., 1997, The motion and boundary between the Capricorn and Australian plates: *Science*, v. 277, p. 1268–1274.
- Royer, J. Y., and Sandwell, D. T., 1989, Evolution of the eastern Indian Ocean since Late Cretaceous: Constraints from Geosat altimetry: *Journal of Geophysical Research*, v. 94, p. 13755–13782.
- Sandwell, D. T., and Smith, W. H. F., 1997, Marine gravity anomaly from Geosat and ERS-1 altimetry: *Journal of Geophysical Research*, v. 102, p. 10039–10054.
- Searle, R. C., 1986, GLORIA investigations of oceanic fracture zones: Comparative study of the transform fault zone: *Geological Society of London Journal*, v. 143, p. 743–756.
- Sempéré, J.-C., and McDonald, K. C., 1987, Marine tectonics: Processes at mid-ocean ridges: *Reviews of Geophysics*, v. 25, n. 6, p. 1313–1347.
- Stein, C. A., Cloetingh, S., and Wortel, R., 1989, Seasat-derived gravity constraints on stress and deformation in the northeastern Indian Ocean: *Geophysical Research Letters*, v. 16, p. 823–826.
- Stein, S., and Okal, E. O., 1978, Seismicity and tectonics of the Ninetyeast Ridge area: Evidence for internal deformation of the Indian plate: *Journal of Geophysical Research*, v. 83, p. 2233–2246.
- Tinnon, M. J., Holt, W. E., and Haines, A. J., 1995, Velocity gradients in the northern Indian Ocean inferred from earthquake moment tensors and relative plate velocities: *Journal of Geophysical Research*, v. 100, p. 24315–24329.
- Van Orman, J., Cochran, J. R., Weissel, J. K., and Jestin, F., 1995, Distribution of shortening between the Indian and Australian plates in the central Indian Ocean: *Earth and Planetary Science Letters*, v. 133, p. 35–46.
- Weissel, J. K., Anderson, R. N., and Geller, C. A., 1980, Deformation of the Indo-Australian plate: *Nature*, v. 287, p. 284–291.
- Wiens, D. A., DeMets, C., Gordon, R. G., Stein, S., Argus, D., Engeln, J. F., Lundgren, P., Quible, D., Stein, C., Weinstein, S., and Woods, D. F., 1985, A diffuse plate boundary model for Indian Ocean tectonics: *Geophysical Research Letters*, v. 12, p. 429–432.

Manuscript received April 15, 1997

Revised manuscript received October 21, 1997

Manuscript accepted November 12, 1997