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 Diament  Institut de Physique du Globe de Paris, Case 89, 4 Place Jussieu, 75252 Paris Cedex 05, France
Hélène Hébert  Ecole Normale Supérieure, 24 rue Lhomond, 75005 Paris, France
Guillaume Bertrand  Laboratoire de Géophysique et Tectonique, Université de Montpellier II, Case 060, 4 place E. Bataillon, 34095 Montpellier Cedex, France
Stéphane Dominguez  ORSTOM, UR14-Laboratoire de Géodynamique sous-marine, B.P. 48, 06230 Villefranche-sur-Mer, France
Jacques Dubois  Institut de Physique du Globe de Paris, Case 89, 4 Place Jussieu, 75252 Paris Cedex 05, France
Jacques Malod  CNRS/Université 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 Géodynamique 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 end of the Ninetyeast aseismic ridge therefore appear 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...
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 Séguinou, 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 southeast 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).

Figure 2. Detailed multibeam bathymetry of area surveyed during Samudra cruise with N60°E 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.

Along the 500 km, the multibeam bathymetry shows that the fault is underlain 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 zones on active spreading centers (Searle, 1986; Sempré 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; Timon 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 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.
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. Sempéré 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


Manuscript received April 15, 1997
Revised manuscript received October 21, 1997
Manuscript accepted November 12, 1997