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Fault reactivation in the central Indian Ocean and the rheology of oceanic lithosphere

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THE intraplate deformation in the central Indian Ocean basin is a well-known example of a deviation from an axiom of plate tectonics: that of rigid plates with deformation concentrated at plate boundaries. Here we present multichannel seismic reflection profiles which show that high-angle reverse faults in the sediments of the central Indian Ocean extend through the crust and possibly into the uppermost mantle. The dip of these faults, which we believe result from the reactivation of pre-existing faults formed at the spreading centre, is ~40° in the basement, which is consistent with the distribution and focal mechanisms of earthquakes on faults now forming at spreading centres. This style of deformation, coupled with the observation of large earthquakes in the mantle lithosphere, indicates that brittle failure of the oceanic lithosphere may nucleate in the vicinity of the brittle/ductile transition and propagate through the crust.

The intraplate deformation occurs in lithosphere of age 60-90 Myr that formed at a fast spreading rate (6 cm yr^{-1}) at the southeast Indian Ocean ridge. It manifests itself as a diffuse zone of compressional and strike-slip earthquakes[1], high localized heat-flow[2], geoid anomalies[3] and tectonic deformation[4,5]. The tectonic deformation can be considered to be occurring on two spatial scales: the first order is represented by long-wavelength (100-300 km), large-amplitude (1-2 km) undulations of oceanic basement and overlying sediments; and the second order by unusual high-angle reverse faults and associated folds in the basement cover. There has been much speculation as to whether the first order of deformation represents buckling[5,6], inverse boudinage[7] or some form of block faulting[8]. The high-angle reverse faults have been less well studied and are the subject of this paper.

The high-angle faults were first documented by Eittreim and Ewing[4] and then further studied by Weissel *et al.*[5] and Geller *et al.*[2]. They found that they offset both basement and overlying sediments, dipped at angles >65° in the sedimentary cover and had a strike of 100° E. Weissel *et al.*[5] suggested that they arose from the reactivation of the pre-existing structural fabric in basement. Recently, results from ODP Leg 116 (ref. 9) have shown that this reactivation started 7 Myr BP and Curray and Munasinghe[10] have shown that the onset of deformation can be correlated over a wide area. Here we discuss results from RRS *Charles Darwin* Cruise 28, during which the first multichannel seismic reflection profiles were collected over the intraplate deformation (Fig. 1). These results not only confirm these previous observations but add important new findings about the character, origin and mode of reactivation of the faults.

The *Darwin* seismic reflection profiles clearly show that the vast majority of the high-angle faults are reverse in nature and few are normal, a conclusion which could not be made from the profiles used by Weissel *et al.*[5]. The reverse faults can be divided into those downthrowing to the north, and those downthrowing to the south. In the survey area approximately equal numbers of faults downthrow in each direction. The new multichannel profiles image (Fig. 2) the faults in basement that dip to the north, their dip being ~35-40° at this depth. In some instances the faults are resolved down to 10-s two-way travel time, roughly the expected level of the oceanic Moho[8,11]. The faults, which appear slightly listric on the time section, are approximately planar after depth conversion. There are additional north-dipping events at lower angles that do not intersect the basement/cover interface that could be other, little reactivated, faults. Faults dipping to the south, on the other hand, are not well resolved. This non-resolution, together with the fact that the offsets of the basement/cover interface on these faults appear nearly vertical, suggests that they may have an appreciably higher angle of dip, probably >45°. Despite this lack of information on some faults, a possible reason for the excellent definition of the faults in basement could be the presence of fluids in the fault planes generating high acoustic-impedance contrasts. The ODP Shipboard Scientific Party[12] believe that the high localized heat flow in this area is associated with hydrothermal circulation within fault blocks, including basement.

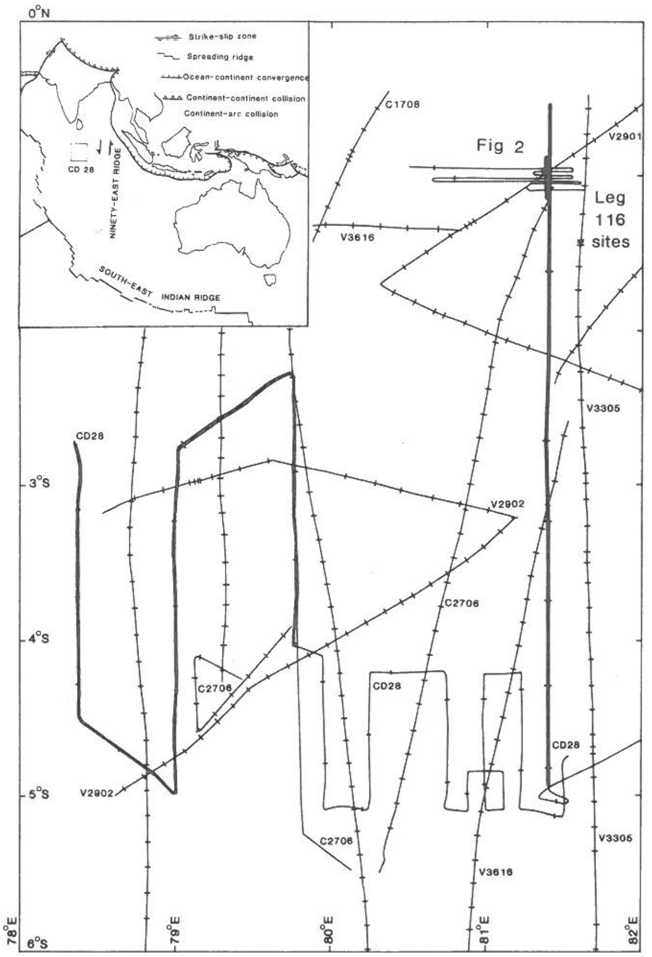

FIG. 1 Position of RRS *Charles Darwin* Cruise 28 in the central Indian Ocean basin together with track chart of seismic profiles which were analysed as part of this work. Plate boundary configuration after Weissel *et al.*[5] with strike-slip motion along the Ninety-east Ridge as suggested by Stein and Okal[21]. Bold lines in the track chart indicate the position of RRS *Charles Darwin* multichannel lines with the position of Fig. 2 indicated.

Around the ODP Leg 116 sites and around 81° E 5° S (Fig. 3), where the density of *Darwin* profiles is high, it is possible to follow a few of the faults along strike for as far as ~40 km. But, more generally, it is not possible to trace faults between lines only 10 km apart, suggesting a mean fault length of <10 km. Where faults could be followed their strike was found to be 90° E to 100° E. This orientation, which is perpendicular to the strike of fracture zones, the manner in which the faults offset basement and their short length giving an en echelon pattern is reminiscent of the fault fabric found parallel to spreading centres. We thus agree with the interpretation of Weissel *et al.*[5] that these faults are the result of the reactivation about 7 Myr BP of the pre-existing spreading-centre-formed fault fabric.

From a statistical and structural analysis of the *Darwin* single-channel seismic profiles and comparison with GLORIA data on the fault fabric of a fast-spreading ridge, the East Pacific Rise[13], Bull[14] demonstrated that the high-angle faults are the

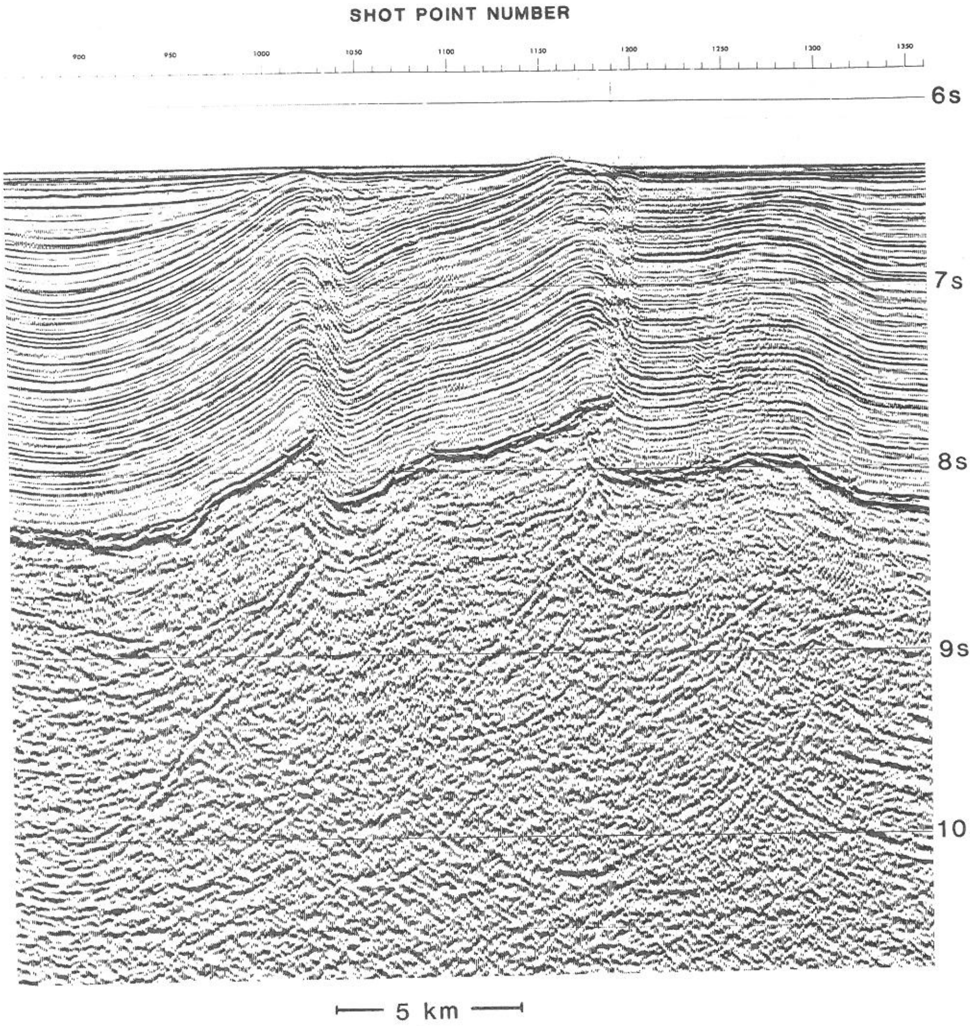

FIG. 2 A short section of fully processed and migrated 12-channel, 12-fold multichannel profile from north (left) to south (right) through the ODP Leg 116 Sites and perpendicular to the structural grain (located A in Fig. 1). Vertical exaggeration is about 3:1 in the sediments and 1.5:1 to 2:1 in basement (the top of which is marked by the strong reflector at ~8-s two-way travel time). Details of the high-angle fault planes in the sediments are evident: some anastomose and show curvature, some are just developing and some are mature. The parallelism of basal sediments and basement suggests basement was originally quite planar and has since been displaced during the intraplate deformation. The fault planes on which the displacement has taken place dip at 30–40° in basement and can be traced to depths at ~10-s two-way travel time (about Moho depth). The multichannel profiles are nearly perpendicular to the strike of the faults and therefore this apparent dip should be close to the true dip. Originally these faults may have been formed at the mid-ocean ridge to the south in which case they must have been outward-dipping faults.

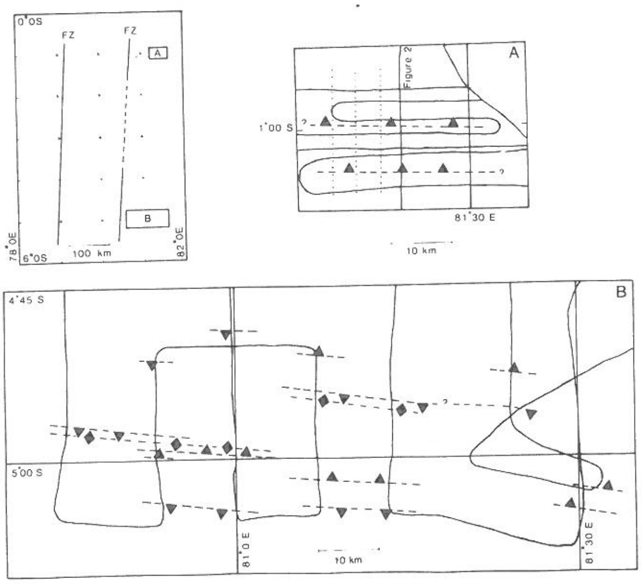

FIG. 3 Plan views of reverse faulting in two areas of the intraplate study area. Top left illustrates the relative positions of the two areas: area A around the ODP Leg 116 sites and area B around 81° E 5° S. The position and orientation of two fracture zones (FZ) developed in the area are also shown. In the detailed maps of area A (top right) and area B (bottom) reverse faults are indicated by dashed lines with a black triangle pointing in the direction of the hanging wall. *Darwin* tracks are continuous lines; in area A the dotted lines are other profiles collected during ODP site surveys and used to constrain the positions of the faults. The position of Fig. 2 is also indicated in area A. In area B the dashed lines with the black diamond ornament show the strike of characteristic hanging-wall anticlines which could be used to tie between lines. It should be noted that, for clarity, not every fault has been annotated in area B: those shown are only the larger ones. In both areas the strike of the reverse faults is 90° E–100° E, roughly perpendicular to the strike of fracture zones (005° E–010° E) developed nearby. The general short fault length (usually <10 km) and resultant en echelon pattern displayed in area B is similar to the fabric developed close to active spreading centres and is consistent with the reverse faults resulting from the reactivation of the pre-existing spreading-centre-formed fabric.

result of the reactivation with reverse movement of two sets of pre-existing spreading-centre-formed normal faults. One of these sets of basement faults dips to the north and therefore faces outwards from the original spreading centre, whereas the other set dips to the south and is the more commonly envisaged inward-dipping set. We have imaged the outward-dipping set with the multichannel seismic profiles, dipping at 35–40° throughout the oceanic crust. The inward-facing set, dipping to the south, which is not resolved in the multichannel data, we infer above is likely to have a higher dip in basement.

An important tectonic implication of these observations is the obvious brittle behaviour of the oceanic lithosphere. The resolution of faults penetrating to at least 10-s two-way travel time indicates that the whole crust and possibly the uppermost mantle is deforming under intraplate compression in a brittle manner. Studies of mid-ocean ridge earthquakes[15-17] have revealed that normal faulting within the median valley occurs on planes that dip at ~45°. Using the assumption that the centroid depth marks the mean depth of fault slip, it seems that faulting extends from 2 to 10 km below the sea floor for these earthquakes—into the upper mantle. Further evidence for the whole crustal extent of spreading-centre-formed faults is found in the western North Atlantic where White *et al.*[18] image eastward-dipping reflectors which they interpret as representing inward-dipping normal faults. It should be noted, however, that these studies of brittle failure have been carried out on crust formed at slow spreading rates; little analogous earthquake work has been carried out on fast-spreading ridges, like the East Pacific Rise, similar to the one that produced the central Indian Ocean basin lithosphere. Nevertheless, it is likely that there is a decrease in the thickness of the brittle layer at fast-spreading ridges in view of the evidence from slow-spreading regions that, in general, brittle layer thickness decreases with increasing spreading rate[15,16]. For large earthquakes the brittle layer may be as little as 3 km thick when spreading rates of 2.5 cm yr^{-1} are reached[16]. Thus it would seem that faulting at the fast-spreading ridge in the Indian Ocean may not have originally penetrated down to Moho and uppermost mantle depths. The deepest parts of the fault planes seen on the multichannel seismic profiles data would then have been formed during reactivation.

Despite the clear evidence for faulting there is a lack of recorded earthquakes associated with the crustal deformation in the central Indian Ocean basin. This could be due to the brittle strength of the oceanic crust and uppermost mantle being too low to sustain significant stresses[19] resulting in only low-magnitude seismicity that is below the level of detection on the worldwide seismograph network. The focal depths of large-magnitude earthquakes recorded in this area are concentrated at depths between 27–39 km (ref. 19), extending down to the expected depth of the brittle/ductile transition. It is interesting that this may be compared with the pattern of continental seismicity in the seismogenic upper crust (see ref. 20, for example) with the largest earthquakes nucleating at or near the base of the brittle layer. By analogy, recent brittle deformation in the central Indian Ocean basin may nucleate at upper-mantle depths and propagate into and through the crust, in the upper part by the reactivation of pre-existing spreading-centre-formed faults. □

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