Refined spreading history at the Southwest Indian Ridge for the last 96 Ma, with the aid of satellite gravity data

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SUMMARY
The spreading history of the oceans is modelled mostly by using magnetic anomalies and the fracture zone geometry. The high-quality, satellite-derived gravity data, that became available in recent years, reveal the details of fracture zones, which can be used as flow lines to control spreading models. We have applied this approach to the Southwest Indian Ridge (SWIR) in order to refine its spreading history. This is particularly useful for the period of complex spreading between magnetic anomalies 33 and 23, where the magnetic anomalies alone cannot resolve the detailed spreading history. We find four main stages in the spreading history of the SWIR since 96 Ma, including two that were not noted previously, between 96 Ma and anomaly 33 (76.3 Ma) and between anomalies 23o (51.7 Ma) and 18o (40.1 Ma; o denotes old boundaries of normal magnetization period). We also find that the start of the period of complex spreading was at anomaly 33, somewhat earlier than previously proposed. We discuss the characteristics of the extension that the old transform faults underwent during the complex spreading phase, in response to the counterclockwise rotation of spreading. New transform faults appeared at that time, considerably widening the transform zones.

Key words: Indian Ocean, Southwest Indian Ridge, spreading, transform faults.

INTRODUCTION
The sea floor morphology of the Southwestern Indian Ocean is dominated by the Southwest Indian Ridge (SWIR), which extends for some 7700 km between the Bouvet triple junction at 55°S, 0.5°W and the Rodrigues triple junction at 25°S, 70°E (Fig. 1). Spreading at the axis of the SWIR started 165 Ma ago with the breakup between Africa and Antarctica (Livermore & Hunter 1996). The early development of the Southwest Indian Ocean, from breakup to anomaly 34 [83 Ma on the magnetic timescale of Cande & Kent (1995)] was poorly resolved until recently. Recent works (Marks & Tikku 2001; Tikku et al. 2002) significantly improved the understanding of the early accretion history and, in particular, resolved the overlap problem of Madagascar Plateau. They also defined the location of Madagascar with respect to Africa and Antarctica. In contrast, the post-chron 34 evolution of the SWIR appeared to be well constrained by the early studies of the region (Norton & Sclater 1979; Patriat 1979; Tapscott et al. 1980; Sclater et al. 1981; Fisher & Sclater 1983; Martin & Hartnady 1986). These generally proposed that a single pole of rotation describes the motion between Africa and Antarctica during the entire period from anomaly 34 to the present. When additional magnetic data were collected in the region, it became apparent that spreading at the SWIR was not constant, but rather quite complex, with periods of rapid spreading and a long period of very slow spreading, which extend to the present time. Consequently, previous, simple, single-rotation pole models were replaced by a series of rotations representing a rather complex spreading history, with significant changes in the direction and rate of spreading (Patriat et al. 1985; Patriat & Séguinou 1988; Royer et al. 1988). These models were mostly based on the identification of the magnetic anomalies and less on the use of fracture zones as indicators of flow lines of the plate motion. This approach was adopted since the fracture zones, although quite prominent in places, appeared to be quite linear, in a marked contrast with the magnetic anomalies, which clearly detailed a complex spreading history at the ridge. Some of these works (Patriat et al. 1985; Patriat & Séguinou 1988) have generally used fracture zones as an overall guide and placed more importance on their trend, only for periods where the magnetic anomalies proved to be insufficient for determining rotation parameters. They noted some inconsistencies and misfits in their models, but related them to fundamental geological processes, such as regional plate deformation and not to a lack of data.

Royer et al. (1988) were the first to use the earliest satellite altimetry data to improve the fracture zone geometry along the SWIR. However, the satellite profiles were not dense enough for precisely following the traces of conjugate fracture zones, particularly in the complex area between 25°E and 35°E where the original trend of the transform faults might have been overprinted by a younger trend.
Figure 1. Vertical gradient gravity map (VDGM; see Rotstein et al. 2001) of the SWIR, based on the free-air gravity data of the Geosat and ERS1 satellites (Sandwell & Smith 1997) showing in detail the transform fault and fracture zone pattern of the SWIR. Also marked on the map are the locations of the bathymetric features discussed in the text. AB = Andrew Bain FZ; M = Marion FZ; PE = Prince Edward FZ and ES = Eric Simpson FZ.
Using Seasat data was clearly an important step towards improving the details of the tectonic fabric of the world ocean floor (e.g. Sandwell & Schubert 1982; Gahagan et al. 1988). However, the quality of the maps at that time was not sufficient to reveal the details of the complex pattern of fracture zones associated with the SWIR because of their dense distribution and nonlinear nature. Since then, the Geosat and ERS1 altimetry missions enabled the construction of a uniform and dense 2′ gravity anomaly grid (McAdoo & Marks 1992; Sandwell & Smith 1997). The 2′ satellite-derived free air gravity map now unveils many details of the structure and segmentation of the SWIR (Marks et al. 1993; Fig. 1). All the fracture zones that were previously observed as bathymetric features (Fisher & Goodwillie 1997) are apparent on this gravity map and can now be traced with significantly more detail and accuracy. Additional small fracture zones can now be recognized between the main fracture zones, achieving a higher resolution of bathymetric detail. Since this work was done, a 1′ satellite grid became available but is not expected to change the results that are presented in this work.

The availability of this new data set and the observation that the details of the accretion on the SWIR since the Late Cretaceous can be better resolved prompted this study. For example, with the new data it became apparent that, although the main evolution stages described previously (Patriat et al. 1985; Patriat & Ségoufin 1988; Royer et al. 1988) are correct, the flow lines that result from previously published poles are at places oblique to the fracture zones. This work attempts to refine the available spreading models of the SWIR since the Late Cretaceous. It uses a more complete set of magnetic anomalies than was previously available. More importantly, it uses the details of the fracture zone geometry as flow-lines in order to constrain the spreading history of the SWIR. The revised rotation parameters are generally similar to those of Patriat & Ségoufin (1988) and Royer et al. (1988), but better account for the details of fracture zone geometry. This is particularly true between anomalies 33 (76.3 Ma) and 23o (51.7 Ma), where the details of the SWIR spreading were previously not resolved as well as they were for the younger period.

In this paper, after a brief review of data and methods, we present computed poles of the oblique spreading period. The rotation parameters by minimizing the misfit between two pairs of homologous intersections of fracture zones with magnetic anomaly lines on conjugate plates. Five poles of rotation at 96 Ma and at anomalies 34y (83 Ma), 33 (76.3 Ma), 23o (51.7 Ma) and 18o (40.1 Ma) were computed with this method (Table 1). During the period between anomalies 33y (73.6 Ma) and 23o, the rotation parameters

**Table 1.** Rotation parameters for the main phases of SWIR history and intermediate poles of the oblique spreading period. The rotation parameters are calculated using (1) Chang’s method (1987) and (2) a least square fit of fracture zones trends for the period of complex spreading. Angles are positive for counterclockwise rotation, and motions are relative to a fixed Africa. Confidence regions for each computed pole are shown in Fig. 11.

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<td>40.1</td>
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<td>−41.4</td>
<td>7.47</td>
<td>1</td>
<td>15.3</td>
<td>−50.4</td>
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<td>23o</td>
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<td>11.3</td>
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<td>11.11</td>
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<td>0.6</td>
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<tr>
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<td>−42.4</td>
<td>12.38</td>
<td>2</td>
<td>−1.8</td>
<td>−41.4</td>
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<tr>
<td>75.5</td>
<td>Prior to 33y</td>
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<td>−40.9</td>
<td>14.03</td>
<td>2</td>
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<tr>
<td>76.3</td>
<td>33</td>
<td>−4.6</td>
<td>−40.6</td>
<td>14.39</td>
<td>1</td>
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<tr>
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<td>1</td>
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underwent large changes, the scarcity of well-identified magnetic anomalies precludes the definition of conjugate points. However, as the fracture zones are well identified on the VDGM, it is still possible to compute the location of the pole of rotation, but not the rotation angle. For this interval we compute three poles at about anomalies 28 (63.1 Ma), 32y (71.1 Ma) and at 75.5 Ma, prior to anomaly 33y. We first reconstruct the SWIR and its fracture zones at anomaly 23o using the Chang (1987) method. Each of the three pole locations is then computed by minimizing the misfit between the flow lines that result from that pole and the corresponding conjugate fracture zones. This procedure is nonlinear and we use a mean square criterion to minimize the sum of distances between the identified portions of fracture zones and the associated flow lines (Le Pichon et al. 1973). The angle of rotation is then estimated from the length of each portion of fracture zone. The corresponding time intervals are constrained by the few magnetic anomalies closest to the boundaries of each of these portions of fracture zones (Table 1).

RESULTS AND DISCUSSION

Main stages in the spreading history of the SWIR

Anomaly 34y (83 Ma) is the oldest identified anomaly before the magnetic quiet period (Figs 2 and 3). However, as spreading in the region started before, we try extending the kinematic reconstructions into the magnetic quiet zone. We identify the early fracture zones in the magnetic quiet period (Figs 2–4) and find that they extend beyond anomaly 34y without a noticeable change in their trend or shape. Farther into the magnetic quiet zone, the fracture zones show a few degree change in trend, indicating a modification of spreading parameters. We choose the point where the trend changes as the oldest reconstruction model, assuming that it is reasonably safe to extrapolate up to this point, using the spreading parameters of anomaly 34y. The age of the change in the trend can be approximated by extrapolating the well-determined spreading parameters of anomalies 34y and 33, assuming that the earlier spreading had approximately the same characteristics. An age of 96 Ma is estimated in this way for the cusp in the fracture zones, and the plate reconstruction for this age is shown in Fig. 4. The proximity in time to anomaly 34 (Fig. 5) and the continuity of the fracture zones from the cusp to anomaly 33, both appear to support the validity of this age approximation. 96 Ma also corresponds to a marked change in spreading parameters in the Southeast Indian Ocean (Müller et al. 2000), which is likely to have left a noticeable mark in the adjacent SWIR, such as the change in its trend of spreading.

Prior to anomaly 33y, our model is in agreement with that of Royer et al. (1988). As noted by these authors, this was a period of intermediate spreading rate and we calculate a half spreading
velocity of about 3 cm yr\(^{-1}\). We find that the change in spreading parameters, leading to the well-known period of slow and complex spreading at the SWIR, started between anomaly 33o and 33y (Figs 2 and 3). This is somewhat earlier than what was previously suggested (Royer et al. 1988) and being a major stage in the evolution of the Southwest Indian Ocean, an updated reconstruction model for anomaly 33 (76.3 Ma) is presented in Fig. 6.

For the complex plate motion between anomalies 33 and 23o we propose a set of three poles (Table 1). These are generally similar to the previously published poles of Royer et al. (1988) but the new flow lines fit better the fracture zone traces (Fig. 7). The new pattern of spreading indicates that the complex spreading period begins with a gradual change of spreading direction and ends with an abrupt change. In the absence of good magnetic anomaly control between anomalies 33 and 23o, the details of the fracture zones become crucial in resolving the spreading history for which a constant spreading rate was assumed. The corresponding kinematic model is consistent with the few magnetic anomalies from this spreading period, and the predicted flow lines generally match the details of the complex fracture zones (Fig. 7).

Complex spreading ended at anomaly 23o (Fig. 8) and slow spreading continued, but with the present direction. This period appears to be contemporaneous with the period of increased velocity of India with respect to Antarctica (Fig. 9) and the related rapid migration of the Rodrigues triple junction eastward in the reference frames of both Africa and Antarctica (Royer et al. 1988; Dyment 1993). The rapid increase in velocity of India with respect to Antarctica started between anomalies 33 and 32o. The sudden slowing down of India at anomaly 23 is associated with the onset of the collision between India and Eurasia (Patriat & Achache 1984), ending at anomaly 20 with welding of the two plates. These major events are likely to have caused the changes in spreading parameters along the adjacent SWIR.

The long period between anomaly 23o and the present can be further divided into two phases. The first one, between anomaly 23o and anomaly 18o (40.1 Ma), is expressed by a series of short but distinct segments of the fracture zones, which exhibit a different trend than at younger ages (Fig. 3). These are apparent only near the Rodrigues triple junction because of the relative position of the poles of rotation during this period. However, a change in the spreading parameters...
Figure 4. Reconstruction of the Southwest Indian Ocean at 96 Ma. Rotation parameters for the India closure are 44.8° N, 207.1° E and 27.2° (Rotstein et al. 2001). Madagascar is in its present location relative to Africa.
Figure 5. Reconstruction of the Southwest Indian Ocean at anomaly 34y (83 Ma). Rotation parameters for the India closure are 7.8°N, 10.9°E and 65.1° (Royer & Sandwell 1989).

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Figure 6. Reconstruction of the Southwest Indian Ocean at anomaly 33 (76.3 Ma), the start of the period of complex spreading phase. Note the continuity of the fracture zones through anomaly 34y, without any change in the trend. A change in the trend is seen further into the basins, indicating a different pole of rotation. We estimate the time of the change to be 96 Ma (see text).
pattern in the Southwest Indian Ocean, some time between anomalies 21 and 15, has been previously suggested (Bergh & Norton 1976) from magnetic anomalies in the Mozambique Basin. Our separate pole for this period roughly corresponds to the period of collision between India and Eurasia.

We have not been able to identify magnetic anomaly 19 and we start the subsequent phase at anomaly 18o (40.1 Ma) and propose that it lasts to the present time (Fig. 10). Seafloor spreading during this entire period can be modelled with the single pole of Patriat & Ségoufin (1988), but a small modification of the pole...
Figure 8. Reconstruction of the Southwest Indian Ocean at anomaly 23o (51.7 Ma), the end of the period of complex spreading and the return to normal spreading. Note that the larger and older transform faults (Andrew Bain, Marion, Prince Edward, Eric Simpson) turned during the phase of complex spreading into wide fracture zones, each including several distinct fractures. A number of new fracture zones also originated at this period in the old crust. Also, note the migration of the Rodrigues triple junction eastward, in the reference frames of both Africa and Antarctica, since anomaly 33, resulting in the rapid growth of the SWIR.
parameters allows us to better follow the fracture zone geometry (Fig. 7).

Restraining and releasing bends on the SWIR transform faults

As Menard & Atwater (1969) first pointed out, the change in the direction of plate motion will induce a component of either tension or compression into an existing transform fault. These effects, which are commonly known as releasing and restraining bends on strike-slip faults, are determined by the sense of rotation coupled with the direction of relative motion across the transform fault. In the particular case of the SWIR, which is characterized by left lateral transform faults, extension will result from a counterclockwise rotation in the direction of sea floor spreading, and compression by a clockwise rotation. In the period of complex spreading, characterized from a counterclockwise rotation of the spreading direction, a component of extension must have affected the SWIR transform faults. Of course, this effect will occur only in older crust and pre-existing transform faults. At the same time, new transform faults that developed in a newly added part of the ridge will not be affected by this extension. For example, Gallieni and Melville fracture zones that were created at the onset and the end of this period, respectively (Dyment 1993; Sauter et al. 1997), did not experience transverse extension as they are in the newly created part of the SWIR resulting from the easterly migration of the triple junction. In contrast, the VDGM map (Fig. 1) shows that the change in the direction of SWIR spreading was accompanied by the appearance of multiple fracture zones across much of the SWIR, replacing the distinct, single trace transform faults. Some 27 new transform faults appeared between 23° E and 43° E, instead of the 10 existing faults at the start of change in the spreading during anomaly 33. This process appears to be particularly apparent in the larger offset transform faults along the SWIR. In the Andrew Bain transform fault, which was the largest transform fault associated with the SWIR, at least five new closely spaced segments appeared with an average width of some 80 km. This is consistent with the observation (Tucholke & Schouten 1989) that, for a constant angle of rotation, the larger the initial fracture offset is, the wider the transform fault zone becomes. Unfortunately, in the absence of sufficient identified magnetic anomaly crossings between anomalies 33 and 23°, it is impossible to determine the individual offset associated with any of these many transform segments. We note that although this phenomenon is clearly more evident in the large offset Andrew Bain transform, it is not limited to the largest transform faults. This observation is in contrast to Ligi et al. (2002) who suggested that broad transforms are only those with a large offset and with an age offset greater than 20 Ma.
Figure 10. Reconstruction of the Southwest Indian Ocean at anomaly 18o (40.1 Ma), approximately at the end of the collision between India and Eurasia and reorganisation of spreading in the Southeastern Indian Ocean. Note, by comparing Figs 8 and 10, the decrease in the rate of the eastwards migration of the Rodrigues triple junction since anomaly 23. The period between anomalies 23 and 18 is characterized by the formation of numerous small, new transform faults close to the Rodrigues triple junction.
CONCLUSIONS

We find four main spreading periods at the SWIR since 96 Ma, each characterized by a noticeably different trend in the fracture zones: between 96 Ma and anomaly 33 (76.3 Ma); the complex spreading period between anomalies 33 and 23o (51.7 Ma); between anomalies 23o and 18o (40.1 Ma) and between anomaly 18o and the present time. A new rotation pole can be attributed to each of these periods, except for the complex spreading period where several poles are needed to describe the variable spreading pattern. The stages in the development of the SWIR were associated with changes in the regional spreading pattern. These include such major events as the start of a rapid separation of India from Antarctica and the rapid migration of the Rodrigues Triple Junction (77 Ma), and the onset and end of the collision of India with Eurasia (approximately 52 and 44 Ma, respectively). The period of complex spreading between anomalies 33 and 23o is characterized by the appearance of many new transform faults in the old parts of the SWIR.

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