The Magofond 2 cruise: a surface and deep-tow survey on the past and present Central Indian Ridge

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Introduction

Tremendous efforts have been recently focused on the study of the Indian Ocean mid-ocean ridge system. The Southeast Indian Ridge, an intermediate spreading center, displays different types of axial morphology and geophysical signature in relation to variations of the underlying mantle temperature (e.g., Cochran et al., 1997; Sempéré et al., 1997; Christie et al., 1998). The Southwest Indian Ridge offers an almost unique opportunity to study the end-member case of ultra-slow seafloor spreading (e.g. Grindlay et al., 1996; Mével et al., 1997, 1998; see also Marine Geophysical Research, special issue: the Southwest Indian Ridge, December 1997). The Rodrigues Triple Junction, where these ridges intersect, has been the subject of several studies (Honsho et al., 1996). In contrast, the more accessible Central Indian Ridge (CIR) has been poorly studied and no systematic bathymetric and geophysical data coverage exists north of 21°S, although it is an attractive target for mid-ocean ridge studies for several reasons. The drastic changes in spreading rate and direction encountered by the CIR during its history, and the geophysical, morphological, and geochemical evidence of a ridge-hotspot interaction in a narrow corridor in the vicinity of the Rodrigues Ridge have partly motivated the Magofond 2 cruise, as has the desire to acquire high-resolution magnetic anomaly records with deep-tow measurements to investigate detailed time variations of the geomagnetic field and the magnetic structure and properties of the oceanic lithosphere.

Cruise operation

The Magofond 2 cruise of *R/V Marion Dufresne* took place between Oct. 11 - Nov. 9, 1998. Operations took place in two areas in the Exclusive Economic Zone of the Republic of Mauritius (Fig. 1), one located on the present CIR axis east of Rodrigues Island, between 18°30'S and 20°S, and the other southeast of Mauritius Island, on oceanic crust created between 50 and 30 Ma at the CIR axis and including a major change of spreading rate and direction and a fossil ridge segment, the Mauritius Fossil Ridge (Patriat, 1987). Data acquired routinely throughout the cruise include multibeam bathymetry and imagery, gravity, scalar and vector surface magnetics. Following recent improvements, the Thomson Marconi Sonar TSM 5265 multibeam echosounder of *the R/V Marion Dufresne* provided remarkable data in terms of spatial resolution and efficiency (about 20 m for a depth of 3000 m at the optimal speed of 15 knots). Data were processed onboard

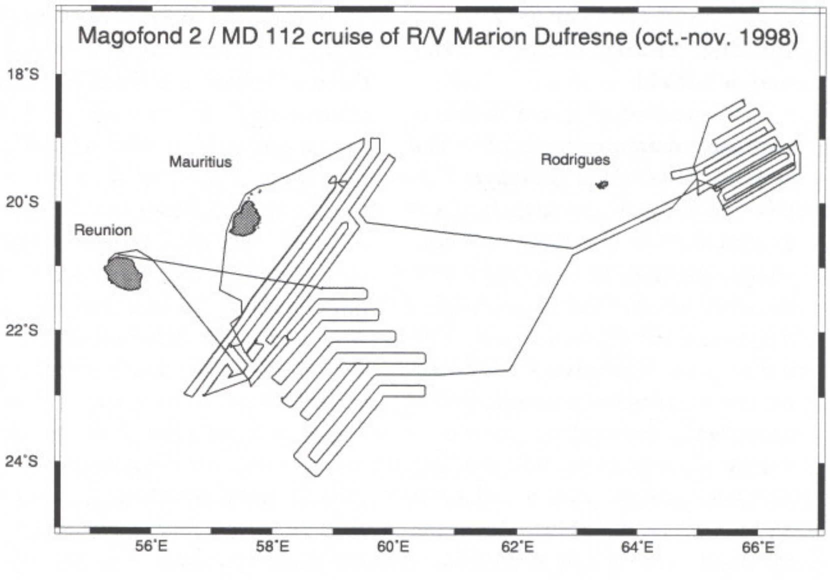

Figure 1: Tracks of the Magofond 2 cruise of *R/V Marion Dufresne*

using the Caraïbes software developed by IFREMER. Gravity measurements obtained by the Lacoste & Romberg marine gravimeter were tied to the reference base of Le Port at Reunion Island using a Scintrex gravimeter, courtesy of colleagues at Université de La Rochelle, France. A proton magnetometer towed 350 m behind the ship at the sea surface provided absolute measurements of the magnetic field intensity and scalar magnetic anomalies. A shipboard three-component magnetometer (STCM) from Ocean Research Institute (ORI), University of Tokyo, Japan, provided vector magnetic anomalies, useful to determine the dimensionality of the magnetized bodies and eventually the direction of the 2D bodies. The surface-towed and shipboard magneto-meters provide complementary information, as the STCM is unable to provide absolute measurements of the magnetic field due to the difficulty to correct adequately for the slowly time-varying viscous magnetization of the ship body. A deep-tow proton magnetometer from ORI was towed about 300-900 m above the seafloor on selected profiles navigated at slow speed (2.5 knots), for a total duration of about 8 days. A new deep-tow Overhauser magnetometer recently purchased by CNRS was also tested during the cruise. Finally, two successful dredge hauls provided about 500 kg of rock samples and sediments.

Detailed history of the Earth's magnetic field

The simplistic view of a binary sequence of alternating polarity and constant intensity is no longer sustainable for the geomagnetic field evolution. The observation of consistent patterns of low-amplitude, short-wavelength anomalies, the tiny wiggles, superimposed on the well-known Vine-Matthews-Morley magnetic anomalies, has been interpreted as reflecting either short polarity reversals or geomagnetic field intensity fluctuations (e.g., Cande and Kent, 1992; Gee et al., 1996). Measurements of geomagnetic field relative paleointensity in sediment cores has also revealed consistent variations for the recent period (e.g., Roberts et al., 1997) and has raised the strongly debated question of the "saw tooth pattern" of the field intensity (e.g., Valet and Meynadier, 1993; Kok and Tauxe, 1996). A good knowledge of the field behavior, both within a given polarity period and in terms of time distribution of the polarity reversals, is essential to investigate the mechanisms of the geodynamo and the dynamics of the Earth core (e.g. Gallet and Courtillot, 1995). For mid-ocean ridge investigators, better constraints on the fine-scale evolution of the geomagnetic field will allow more accurate and unambiguous ages of the seafloor (see, for example, Dyment, 1998), although a limitation may arise from the ability of the oceanic crust to preserve the record of the fine geomagnetic fluctuations.

Surface magnetic anomalies lack the resolution required to unambiguously discriminate the origin of the tiny wiggles, i.e. short polarity reversals or intensity fluctuations, and to obtain a detailed record of the geomagnetic variations. A better resolution can only be achieved by getting measurements closer to the seafloor, using a deep-tow magnetometer. A major objective of the Magofond program is to test the practicality of this approach and to evaluate the potential of such deep-tow magnetic studies for geomagnetic studies. For the sake of comparison with relative paleointen-sity records obtained from sediments, the period investigated spans the last three millions years, i.e. the profiles are collected at a mid-ocean ridge. Another advantage of such a choice is to allow the collection of conjugate profiles and therefore the identification of tectonic complexities unrelated to geomagnetic fluctuations. As for the selection of a target area, a faster spreading rate would insure a better resolution, a slower spreading rate a longer time interval surveyed for the available ship time. In addition, previous works on surface magnetic anomalies suggest that the magnetic structure of the oceanic crust is more complex at a slow/cold spreading center than at a fast/hot one (e.g., Dyment and Arkani-Hamed, 1995; Dyment et al., 1997; Dyment and Fulop, 1997). Despite a relatively slow (full) rate of 45 km/m.y., the part of the CIR located between 18 and 20°S is characterized by a low roughness both on the few available bathymetric profiles and on gravity anomaly maps derived from satellite altimetry (Sandwell and Smith, 1995), typical of oceanic crust formed at a hot, magmatic spreading center. Three deep-tow profiles have been run across the CIR in this area up to about 3 Ma on both flanks, providing six records of the geomagnetic history for the last three millions years.

Fig. 2 shows surface and deep-tow magnetic data collected on Deep Tow Profile 5, which crossed the CIR axis at 19°10'S. The raw magnetic measurements have been reduced for the provisional IGRF model. No correction has been made for the varying altitude of the instrument, the topographic effect, the inclinations of both geomagnetic field and magnetization vectors (which result in the skewness of the anomalies), or time variations such as the diurnal solar quiet variation. Despite these effects, to be corrected in future works, and considering a high on one flank to be matched with a low on the other flank to account for the skewness of the anomalies, a good correlation is observed between both major anomalies and tiny wiggles on conjugate flanks, as suggested by lines connecting various features of the Brunhes anomaly. The best resolution for these conjugate features is 50-100 k.y. for the altitude of 300 m. The Cobb Mountain event is observed on both flanks in the surface and deep-tow data, the Reunion event is well-marked on the northeastern flank and is more subdued on the southwestern one. Spreading is clearly asymmetrical during the Brunhes and Matuyama periods on this profile, with 45% of the crust formed on the African plate and 55% on the Indian plate, but this asymmetry does not affect the correspondence observed between conjugate magnetic features. The data collected on Deep Tow Profiles 3 and 4 are very similar to those of Fig. 2. These data await further processing in order to be compared to relative paleointensity records deduced from the analysis of sediment cores.

Additional deep-tow magnetic data were collected during the Magofond 2. The short Deep Tow Profile 6 surveyed anomalies 4A, 5 and 5A about 1000 m above the seafloor on the African plate. It shows tiny wiggles consistent with those described by Blakely (1974) and, more recently, by Cande et al. (1995) from data collected in the Pacific Ocean off North America, suggesting that global geomagnetic events were responsible for these tiny wiggles. The long Deep Tow Profile 1-2 cut across the Mauritius Fossil Ridge (MFR) and surveyed conjugate anomalies 22 reversed to 20 reversed about 1000 m above the seafloor. No definitive evidence has been found on the unprocessed data for a short normal event within anomaly 22 reversed, as suggested by Patriat (1987) from the observation of a clear tiny wiggle within this anomaly.

Structure and magnetic properties of the oceanic crust

The classical view of rectangular prisms bearing constant magnetization has given place to more complex models, including a geometry of the extrusive basalt layer which results from spreading and lava flow piling (e.g., Kidd, 1977; Macdonald et al., 1983; Tivey, 1996), deeper magnetized layers gently sloping away from the ridge (e.g., Kidd, 1977; Cande and Kent, 1978; Arkani-Hamed, 1989; Dyment et al., 1997), magnetization intensity varying with iron content and fractionation at regional and segment scale, or with alteration at faulted areas or hydrothermal sites (e.g. Hussenoeder et al., 1996; Tivey, 1996). The collection of magnetic data at the sea surface and near the seafloor can help to resolve the structure and magnetic properties of the oceanic crust.

The anomalous skewness of surface magnetic anomalies decreases with spreading rate, from a negligible value above 50 km/m.y. (half rate) to as much as 40° at about 10 km/m.y. (Dyment et al., 1994). This observation suggests that the source of the anomalies is almost exclusively made of a thick layer of iron rich, strongly magnetized extrusive basalt for fast-spreading centers. Conversely, a deeper magnetic layer, possibly made of partly serpentinized lower crustal rocks, would increasingly contribute to the anomalies as the extrusive basalt gets thinner, more pervasively altered, and less magnetized with decreasing spreading rate (Dyment and Arkani-Hamed, 1995; Dyment et al., 1997). In order to test this model and investigate the relative contribution of the shallower and deeper magnetized layers at different spreading rates, a long deep tow magnetic profile has been navigated across the MFR between conjugate anomalies 23 (young side, 51 Ma) and anomaly 20 reversed (43 Ma), which marks the end of spreading activity. The advantage of such a fossil ridge is twofold: the proximity of conjugate anomalies makes the anomalous skewness easier to evaluate, and the progressive decrease of spreading rate allows to investigate the effect of this parameter. Magnetic measurements at the sea surface, 4000 m above the seafloor, detect with four times more intensity a magnetized source located in the extrusive basalt layer than the same source in the lower crust; this ratio increases to twenty for deep-tow magnetic measurements made 1000 m above the seafloor. The joint analysis of surface and deep-tow data (after altitude and topography corrections, see above) for both skewness and amplitude should provide better constraints on the relative contribution of shallower and deeper magnetized layers, and therefore on the source of marine magnetic anomalies at different spreading rates. Preliminary results indicate is a sharp decrease in the anomaly amplitude at anomaly 21r, which corresponds to spreading rates falling from 40 to 20 km/m.y. and a rapid transition between smooth and rough bathymetry (Fig. 3). A similar observation has been obtained from a systematic analysis of anomaly 25 in the world's ocean basins (Dyment and Fulop, 1997), with a clear separation of low and high anomaly amplitudes at a spreading rate of 30 km/Ma. This threshold, which roughly corresponds to the morphological transition between axial valleys and axial domes, may reflect changes in the extrusive layer

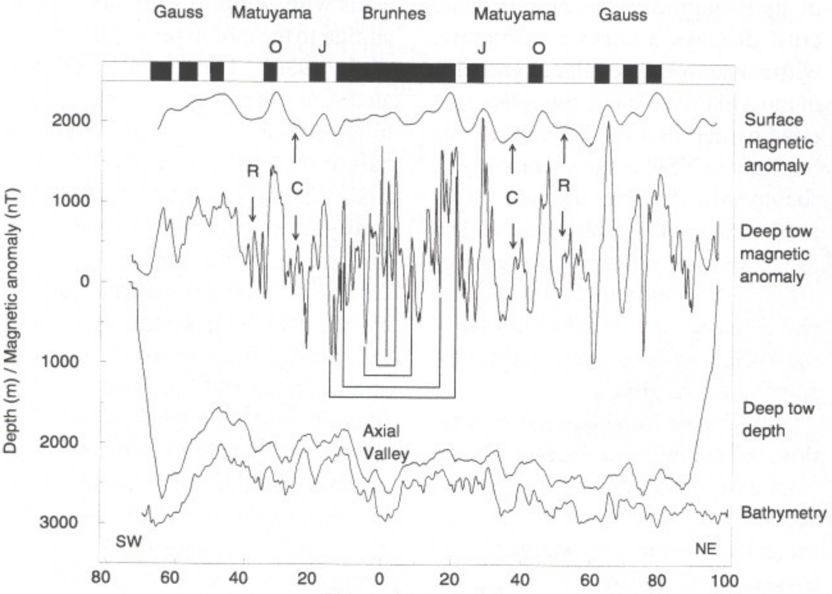

Figure 2: Surface and deep tow magnetic anomalies, deep tow depth and bathymetry across the Central Indian Ridge at 19°10'S. Normal (reversed) magnetic polarity intervals are shown in black (white), with J: Jaramillo, O: Olduvai; possible short events marked by tiny wiggles are shown by arrows, with R: Reunion, C: Cobb Mountain. Thin lines connect short-wavelength conjugate features inside the Brunhes period.

thickness, in the degree of alteration, or in the iron content of the extrusive basalt.

A drastic change of spreading direction between 45 and 40 Ma

A major reorganization of the Indian Ocean mid-ocean ridge system occurred between 45 and 40 Ma (anomalies 20 to 18) as a possible consequence of the collision of India with Eurasia (e.g., Patriat and Achache, 1984). On the CIR this event is marked by a rapid decrease of spreading rate followed by a 50° clockwise change of spreading direction. In an attempt to understand the detailed evolution of such a large reorganization, we surveyed two key-areas on the African plate southeast of Mauritius (Fig. 4). Data on parts of the conjugate area on the Indian plate have been acquired by our Indian colleagues of the National Institute of Oceanography, Goa, India.

The first area is located southeast of the Mauritius Fracture Zone. Prior to anomaly 20 reversed (43 Ma), it was part of a relatively narrow compartment, about 100 km wide, bounded by large offset transform faults. In this area, the reorganization is marked by a sharp decrease of spreading rate at anomaly 21 reversed (48 Ma; see above and Fig. 3), clearly seen in the increasing roughness of the bathymetric fabric (Fig. 4), and the cessation of spreading at anomaly 20 reversed (44 Ma) on a 80 km long section of the CIR, now the MFR, which displays a large and deep axial valley filled with sediments. Deformation, breakup and finally the initiation of a new spreading center occurred along a N30°E lineament, which isolated and transferred a 300 km-long, 80 km-wide sliver of oceanic crust originally formed on the Indian plate to the African plate. The linearity and morphology of this feature as well as its direction may have led some confusion with a fracture zone; this interpretation is however not sustainable, as no conjugate feature exists on the southern flank of the MFR. The N120°E fabric of the older crust, clearly seen on the southeastern part of the transferred crust sliver although it is covered by sediments on most of its extent, is cut across by N170°E deformational features. The "scar" between the old and new oceanic crust is made of a trough, filled by sediments, and a linear, quite continuous ridge, suggesting a strike-slip motion component in the early stage of its evolution. The new oceanic crust displays a complex structure, with at least four irregular alignments of most likely volcanic mounds separated by depressions. These features trend about N50°E and seem to curve southward and tangent the "scar". Our preliminary interpretation considers the mounds as short ridge segments offset by discontinuities (the depressions) to account for the obliquity of the "scar" with respect to the new spreading direction.

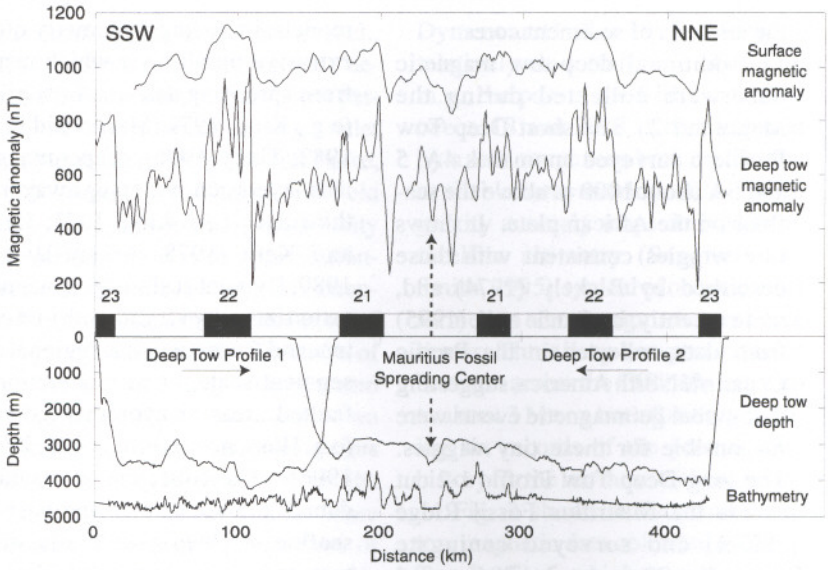

Figure 3: 30° phase-shifted furface and deep tow magnetic anomalies, deep tow depth and bathymetry across the Mauritius Fossil Ridge. Normal (reversed) magnetic polarity intervals are shown in black (white). Note the symmetry of the conjugate flanks and the decreasing anomaly amplitude for anomalies younger than 21 reversed.

Prior to the spreading reorganization, the second area, located further southeast, represented a continuous section of a fast-spreading center, more than 300 km-long, only affected by small offset discontinuities. The decreasing spreading rates are associated with a more segmented bathymetric fabric and a rougher bathymetry, although the change appears more progressive than on the first area. Although the detailed interpretation of the magnetic anomaly is not yet available, the various trends of the bathymetric fabric clearly show that the change of direction is not synchronous. New segments, about 10 to 20° oblique to the previous direction, appears in the vicinity of the fracture zones and propagate at the expense of the older fabric or areas with complex structures, quite similar to the model proposed by Hey et al. (1988). This process is reiterated 3 or 4 times to achieve the 50° total rotation, as seen in the central part of the survey area (Fig. 4). The first-order segmentation is also drastically affected by the reorganization. The major fracture zone system at 22°S, 58°E, named La Boussole FZ by Patriat (1987), is actually made of two nearby fracture zones between anomalies 23 and 21. The southern fracture zone disappears after a 20° rotation of the nearby fabric has been achieved, and the northern one evolves to a second-order discontinuity after 40°. This observation possibly reflects the progressive decrease of the offset across this feature as a result of the ridge segment clockwise reorientation revealed by the bathymetric fabric. At the same time, the coalescence of several oblique discontinuities, which becomes more or less parallel to the spreading direction due to the progressive rotation of this direction, results in the creation of a new N80°E fracture zone. Such a fracture zone may be required by the increasing offset induced by the clockwise reorientation of the segments.

The establishment of a more detailed evolution of these events and its chronology awaits further structural analyses and the integrated analysis of the new and previous surface magnetic anomaly data available in the area.

Ridge-hotspot interaction: the CIR at 19°S

The CIR presents morphological and geophysical evidence of a hotter mantle in the vicinity of Rodrigues Ridge, between the Marie-Celeste and Egeria Fracture Zones (18°S-20°S). Geochemical analyses of the few available samples along the CIR also suggest a narrow corridor where the MORBs are contaminated by hotspot material showing affinities with the Reunion hotspot (Mahoney et al., 1989; Humler, pers. comm.). These inferences are most likely related to the nearby Rodrigues Ridge, an off-axis bathymetric structure which extends continuously from the Mascarene Plateau to the Rodrigues Island area along a roughly N105°E direction and overlays oceanic crust created from 40 to 7 Ma. Samples dredged on the ridge have provided rather uniform ages of 7-9 Ma (Baxter, pers. comm.). Our investigation on the CIR at 19°S, triggered by a favorable setting to collect deep-tow magnetic data, provides an opportunity to study a slow-spreading center (half spreading rate 2.2 km/m.y.) in a hot mantle environment and, more generally, the interaction of this ridge with the hotspot from which the Rodrigues Ridge originated.

We have collected the full bathymetric coverage of a 150 km-long section of the CIR from the ridge axis to anomaly 2A included (4 Ma) on both flanks, with extension to anomaly 3A (7 Ma) in the close vicinity of the Rodrigues Ridge (Fig. 5). The ridge axis is made of a shallow axial valley, with inner floor 3000 m deep and crests 2200 m deep. The

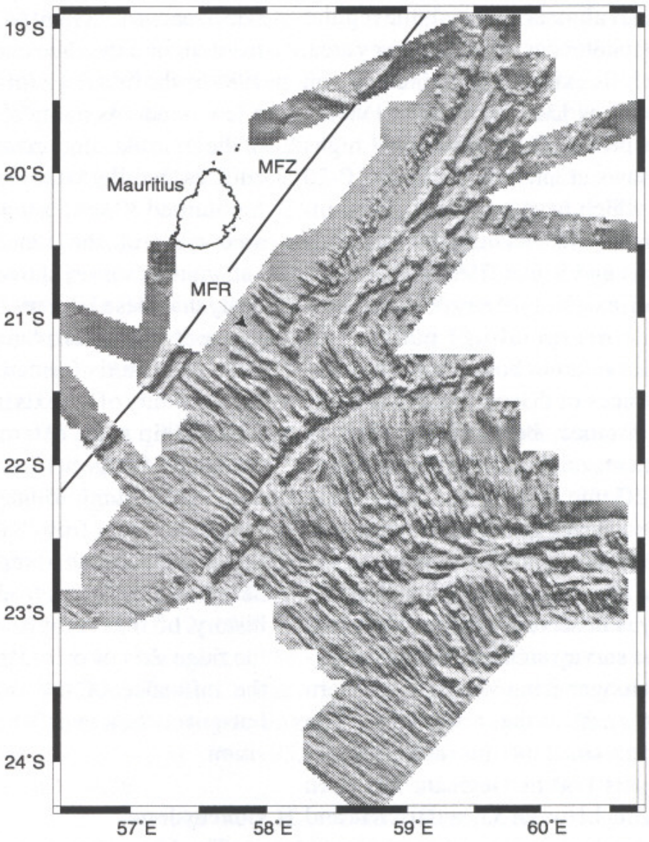

Figure 4: Shaded bathymetry of the Mauritius Fossil Ridge (MFR) and the change of spreading direction, dated 40-45 Ma, in the vicinity of Mauritius and Reunion Islands (illumination from North). MFZ: Mauritius Fracture Zone. See text for details.

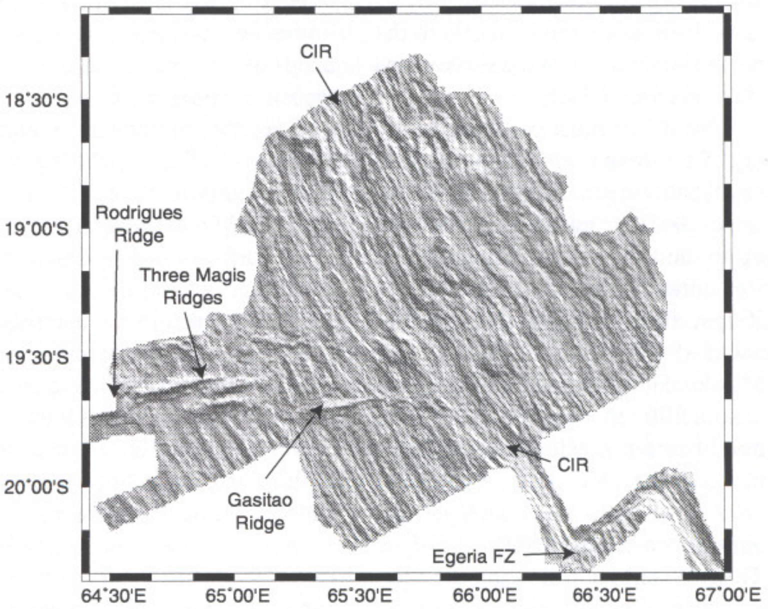

Figure 5: Shaded bathymetry of the Central Indian Ridge (CIR) in the vicinity of the Rodrigues Ridge (illumination from N60°W) from *R/V Marion Dufresne* Magofond 2 cruise and *R/V L'Atalante* Larjaka transit data. Note the shallow axial valley, the continuous abyssal hills, the discontinuity at the northern end of the survey, and the Three Magi and Gasitao Ridges which connect the easternmost end of the Rodrigues Ridge with the CIR axis.

off-axis abyssal hills are quite regular and monotonous along the survey area, with hills extending continuously on as much as 130 km. The axial valley floor presents a succession of highs and lows at intervals of about 10-20 km, which have previously been interpreted as segment centers and ends (Briais and Sauter, 1998). However, the off-axis bathymetry does not show the corresponding pattern of rhombohedrons bounded by continuous traces of discontinuities as seen, for instance, between neighboring segments on the Mid-Atlantic Ridge (e.g., Gente et al., 1995), suggesting that no stable short-wavelength segmentation exists in most of the survey area. The only continuous discontinuity is observed at the northern end of the survey area and bounds a segment longer than 130 km (its southern limit is outside the survey area). The varying trend of this discontinuity suggests that the segment has been growing between 3.5 and 0.7 Ma and may have recently started to recede. This pattern of segmentation, with long segments and minor, transient discontinuities inside, may reflect a better magma supply and hotter asthenosphere, in contrast with the smaller segments, 80 km long in average, observed on the CIR axis to the north and the south of the survey area (Parson et al., 1993).

One of the most striking discovery of the Magofond 2 is a series of small bathymetric ridges which continues the Rodrigues Ridge eastward up to the CIR on the African flank. Immediately east of the Rodrigues Ridge, three parallel ridges trend about N80°E on oceanic crust 6.5 to 4 Ma old. These ridges, 20-40 km long and 1500 m higher than the neighboring seafloor, have been named "The Three Magi Ridges" to emphasize their linear and parallel appearance, similar to the paths of the Three Wise Men following the Star. Further east, another ridge, parallel to the previous ones and also remarkably linear, lies on oceanic crust 3.5 to 0.5 Ma old and ends on the western crest of the CIR axial valley. This ridge, 50 km long and 700 m higher than the neighboring seafloor, has been named "Gasitao Ridge" in memory of a cyclone encountered in 1988 by the first *R/V Marion Dufresne* a few hundreds nautical miles north of the area. An alignment of volcanic edifices, parallel to the Gasitao Ridge, is observed 30 km northward, on oceanic crust of the same age. Our bathymetric survey shows unambiguously that these features have no conjugate on the Indian plate, which suggests an off-axis formation although the proximity of the axis implies some relationship to be determined. Two successful dredge hauls on the Gasitao and Three Magi Ridges have provided relatively fresh basalt, including glass. These samples will be dated and analyzed to decipher the history of their emplacement (near the ridge axis or on older crust?) and the influence of the ridge and the hotspot on their geochemical composition.

Conclusions

The Magofond 2 cruise has provided a collection of excellent data which, after only a preliminary analysis, lead to the following results:

1) Although this inference awaits further processing to correct for the effects of topography and varying immersion of the magnetometer, our deep-tow magnetic measurements record a coherent signal (as illustrated by the comparison of conjugate profiles, see Fig. 2. which partly reflects time-variations of the geomagnetic field at a scale of 100 k.y.

2) Surface and deep-tow magnetic anomalies across the MFR reveal a strong decrease in the anomaly amplitude at a (half) spreading rate of about 30 km/m.y. which reflects important differences in the thickness, degree of alteration, or iron content of the extrusive basalt between fast- and slow-spreading centers.

3) Our off-axis bathymetric survey of the MFR and the nearby remnants of the 40-45 Ma spreading reorganization reveals the reaction of a spreading center to the remote collision of India with Eurasia and its effect on plate kinematics. In the western area, a ridge section died and a new one was initiated, while in the eastern area, a progressive readjustment ocurred through propagating ridge segments, eliminating a fracture zone and creating a new one.

4) The CIR at 19°S is a slow and hot spreading center, with morphological, geophysical and geochemical characters contrasting with those observed elsewhere on the CIR. Despite the unclear origin of the Rodrigues Ridge, ridge-hotspot interaction still exists in this area, as suggested by the newly discovered Three Magi and Gasitao Ridges which continue the Rodrigues Ridge eastward up to the CIR axis.

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References

Arkani-Hamed, J., Thermoviscous remanent magnetization of oceanic lithosphere inferred from its thermal evolution, *J. Geophys. Res.*, 94, 17,421-17,436, 1989.

Blakely, R., Geomagnetic reversals and crustal spreading rate during the Miocene, *J. Geophys. Res.*, 79, 2979-2985, 1974.

Briais, A. and D. Sauter, Influence of the Reunion hotspot on the accretion at the Central Indian Ridge 18.5S 25.5S inferred from mantle Bouguer anomaly analysis, *EOS Trans. AGU*, 79, F918, 1998.

Cande, S.C., and D.V. Kent, Constraints imposed by the shape of marine magnetic anomalieson the magnetic source, *J. Geophys. Res.*, 81, 4157-4162, 1976.

Cande, S.C. and D.V. Kent, 1992, Ultrahigh resolution marine magnetic anomaly profiles: a record of continuous paleointensity variations?, *J. Geophys. Res.*, 97, 15,075-15,083.

Cande, S.C., J.A. Hildebrand, R.L. Parker, N.E. Bowers and T. Fujiwara, A deep tow survey of anomaly 5 in the Northeast Pacific reveals a high resolution recording of geomagnetic field behavior, *EOS Trans. AGU*, 76, F169, 1995.

Christie, D.M., B.P. West, D.G. Pyle and B.B. Hanan, Chaotic topography, mantle flow and mantle migration in the Australian-Antarctic discordance, *Nature*, 394, 637-644, 1998.

Cochran, J.R., J.C. Sempéré, and SEIR Scientific Team, The Southeast Indian Ridge between 88°E and 118°E: Gravity anomalies and crustal accretion at intermediate spreading rates, *J. Geophys. Res.*, 102, 15 463-15 488, 1997.

Dyment, J., S.C. Cande and J. Arkani-Hamed, Skewness of marine magnetic anomalies created between 85 and 40 Ma in the Indian Ocean, *J. Geophys. Res.*, 99, 24,121-24,134, 1994.

Dyment, J. and J. Arkani-Hamed, Spreading rate dependent magnetization of the oceanic lithosphere inferred from the anomalous skewness of marine magnetic anomalies, *Geophys. J. Int.*, 121, 789-804, 1995.

Dyment, J., J. Arkani-Hamed, and A. Ghods, Contribution of serpentinized ultramafics to marine magnetic anomalies at slow and intermediate spreading centers: insights from the shape of the anomalies, *Geophys. J. Int.*, 129, 691-701, 1997.

Dyment, J. and A. Fulop, Variations of magnetic anomaly shape and amplitude with spreading rate, implications for the magnetic structure and properties of the oceanic lithosphere, *EOS Trans., AGU*, 78, F664, 1997.

Dyment, J., Evolution of the Carlsberg Ridge between 60 and 45 Ma: ridge propagation, spreading asymmetry, and the Deccan-Reunion hotspot. *J. Geophys. Res.*, 103, 24067-24084, 1998.

Gallet, Y. and V. Courtillot, Geomagnetic reversal behaviour since 100 Ma, *Phys. Earth Planet. Int.*, 92, 235-244, 1995.

Gee, J., D.A. Schneider and D.V. Kent, Marine magnetic anomalies as recorders of geomagnetic intensity variations, *Earth Planet. Sci. Lett.*, 144, 327-335, 1996.

Gente, P., R.A. Pockalny, C. Durand, C. Deplus, M. Maia, G. Ceuleneer, C. Mével, M. Cannat and C. Laverne, Characteristics and evolution of the segmentation of the MAR between 20°N and 24°N during the last 10 millions years, *Earth Planet. Sci. Lett.*, 129, 55-71, 1995.

Grindlay, N., J.A. Madsen, C. Rommevaux, J.G. Sclater and S. Murphy, Southwest Indian Ridge 15°E-35°E: a geophysical investigation of an ultra-slow spreading mid-ocean ridge system, *InterRidge News*, 5(2), 7-12, 1996.

Hey, R.N., H.W. Menard, T.M. Atwater and D.W. Caress, Changes in direction of seafloor spreading revisited, *J. Geophys. Res.*, 93, 2803-2811, 1988.

Honsho, C., K. Tamaki and H. Fujimoto, Three-dimensional magnetic and gravity studies of the Rodriguez Triple Junction in the Indian Ocean, *J. Geophys. Res.*, 101, 15.837-15.848, 1996.

Hussenoeder, S.A., M.A. Tivey, H. Schouten, and R.C. Searle, Near-bottom magnetic survey of the MAR axis, 24°-24°40'N: Implications for crustal accretion at slow spreading ridges, *J. Geophys. Res.*, 101, 22,051-22,069, 1996.

Kidd, R.G.W., The nature and shape of the sources of marine magnetic anomalies, *Earth Planet. Sci. Lett.*, 33:310-320, 1977.

Kok, Y.S. and L. Tauxe, Saw-toothed pattern of relative paleointensity records and cumulative viscous remanence, *Earth Planet. Sci. Lett.*, 137, 95-99, 1996.

Macdonald K.C., S.P. Miller, B.P. Luyendyck, T.M. Atwater and L. Shure, Investigation of a Vine-Matthews magnetic lineation from a submersible: the source and character of marine magnetic anomalies, *J. Geophys. Res.*, 88, 3403-3418, 1983.

Mahoney, J.J., J.H. Natland, W.M. White, R. Poreda, S.H. Bloomer, R.L. Fisher and A.N. Baxter, Isotopic and geochemic provinces of the Western Indian Ocean spreading centers, *J. Geophys. Res.*, 94, 4033-4052, 1989.

Mével, C. et al. Sampling the Southwest Indian Ridge: first results of the EDUL cruise, *InterRidge News*, 6(2), 25-26, 1997.

Mével, C., K. Tamaki, and the Fuji Scientific Party, Imaging an ultra-slow spreading ridge: first results of the FUJI cruise on the SWIR, *InterRidge News*, 7(1), 29-32, 1998.

Parson, L.M., P. Patriat, R.C., Searle, and A.R. Briais, Segmentation of the CIR between 12°12'S and the Indian Ocean Triple Junction, *Mar. Geophys. Res.*, 15, 265-282, 1993.

Patriat, P., Reconstitution de l'évolution du système de dorsales de l'océan Indien par les méthodes de la cinématique des plaques, 308 pp., Territoire des Terres Australes et Antarctiques Françaises, Mission de Recherche, Paris, 1987.

Patriat, P., and J. Achache, India-Eurasia collision chronology has implications for crustal shortening and driving mechanism of plates, *Nature*, 311, 615-621, 1984.

Roberts, A.P., B. Lehman, R.J. Weeks, K.L. Verosub and C. Laj, Relative paleointensity of the geomagnetic field over the last 200,000 years from ODP Sites 883 and 884, North Pacific Ocean, *Earth Planet. Sci. Lett.*, 152, 11-23, 1997.

Sandwell D.T. and W.H.F. Smith, Free-air gravity anomaly derived from satellite altimetry over the World's Oceans map, Scripps Inst. Ocean., La Jolla, Calif., 1995.

Sempéré, J.-C., J.R. Cochran, and SEIR Scientific Team, The Southeast Indian Ridge between 88°E and 118°E: variations in crustal accretion at constant spreading rate, *J. Geophys. Res.*, 102, 15 489-15 506, 1997.

Tivey, M.A., Vertical magnetic structure of ocean crust determined from near-bottom magnetic field measurements, *J. Geophys. Res.*, 101, 20275-20296, 1996.

Valet, J.P. and L. Meynadier, Geomagnetic field intensity and reversals during the past four million years, *Nature*, 366, 234-238, 1993.