

Deep-sea Exploration of the Central Indian Ridge at 19°S

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Introduction

Among the World's mid-ocean ridge system, the Indian Ocean spreading centres have been poorly studied by direct deep-sea exploration. In May-June 2000, the first dives of deep-sea submersible *Nautilie* in the Indian Ocean, and the second ever manned deep-sea submersible in this ocean (see Fujimoto *et al.*, 1999), were carried out during the cruise GIMNAUT of *R/V L'Atalante* on the Central Indian Ridge (CIR) at 19°S. Cruise GIMNAUT (acronym for Geochronology, ridge-hotspot Interaction, Magnetism with *NAUTile*) departed Mauritius Island on May 14th, 2000 and ended in

Reunion Island on June 7th, 2000 (Fig. 1). The main objective of this cruise was to address the problem of accurate dating methods for recent processes at mid-ocean ridges, paying particular attention to;

- the combined use of existing short-lived isotope dating methods and K-Ar method for recent Mid-Ocean Ridge Basalt and their intercalibration for the overlapping period. Producing reliable ages is essential to study the magmatic and tectonic processes at mid-ocean ridges; and
- the observation of a dated, continuous sequence of recent geomagnetic intensity variations through the acquisition of near-bot-

tom anomalies and measurement of paleointensity on rock samples.

If the oceanic crust accurately records the relatively well-known sequence of these variations, deep-sea magnetism may ultimately be used to date the ocean floor at high resolution (10-100 ka), on a small-scale replication of what is classically done with surface magnetism at a resolution of a million years.

The CIR at the latitude of Rodrigues Ridge (19°S) is a good target to address this topic because rock samples are enriched in trace elements (Engel and Fisher, 1975; Mahoney *et al.*, 1989; Humler, pers. comm.) and this is of great help in achieving optimal accuracy on the

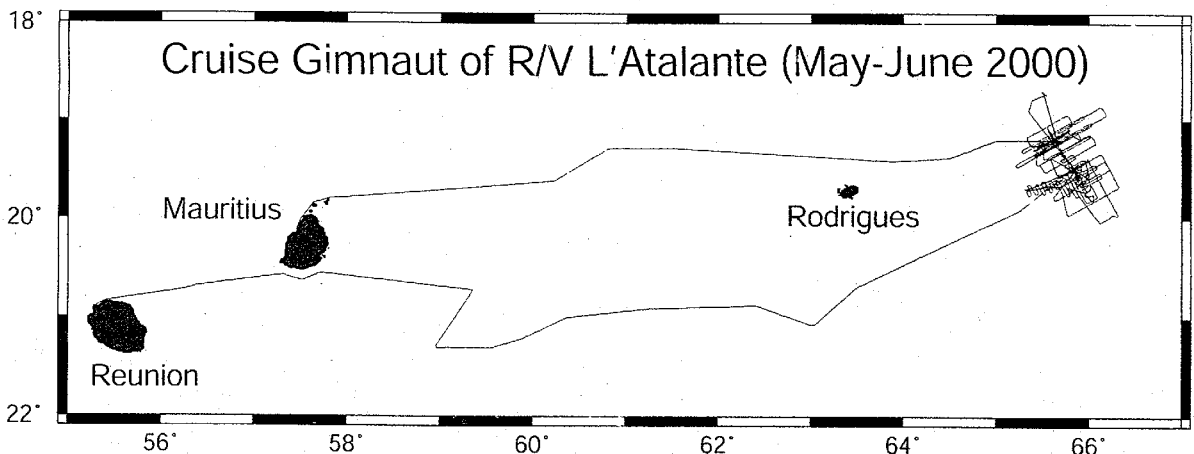


Figure 1. Tracks of the GIMNAUT cruise

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ages. Moreover, the full multibeam bathymetric data coverage acquired at the axis up to about 3 Ma during the MAGOFOND 2 cruise (Dymant *et al.*, 1999) was essential in the preparation of each dive. In addition, this area provides the opportunity to study a slow to intermediate spreading centre overlying a hot mantle, in the framework of its interaction with a hotspot, presumably the Reunion hotspot (Morgan, 1978; Engel and Fisher, 1975; Mahoney *et al.*, 1989; Dymant, 1999).

Dive operations and preliminary results

We carried out two transects on the CIR from the axis to the Brunhes-Matuyama magnetic polarity boundaries (about 800 ka), on both the African and Indian flanks (Figs. 2 & 3). These transects intersected the CIR axis at 19°11'S (9 dives,

designed as the "northern section") and at 19°29'S (8 dives, designed as the "southern section"), respectively. Three additional dives were devoted to further exploration of the CIR axis. The following techniques of investigation were applied during the *Nautilie* dives:

- direct visual observation of tectonic and volcanic structures and of the different types of lithology, using video records (~100 hours) and photography (> 4000);
- continuous acquisition of vector magnetic data with a deep-sea three-components magnetometer (Ocean Research Institute, Tokyo) was successfully carried out on 17 dives. Sea-water turbidity was acquired with a nephelometer (IFREMER DRO-GM, Brest) on the first dive;
- punctual measurements of gravity data on the seafloor (29 stations on 13 dives);

- and collection of rock samples dedicated to petrological, geochemical and rock magnetic analyses.

About 150 sites were sampled. The first petrological descriptions and initial measurements of the Natural Remanent Magnetization were carried out onboard. Further measurements, such as isotope ratios, short-lived isotope and K-Ar dating, as well as determinations of absolute magnetic paleointensity, will be carried out in the future. This large data set will need to undergo detailed analyses in the next few years, before any solid conclusions can be established, and the major objectives of the GIMNAUT cruise addressed. However, the initial observations elucidate some preliminary characteristics of the CIR at 19°S;

- all of the observed and sampled rocks are basalts, with a majority of pillow lava and a significant number of dykes. No mafic or ultramafic rocks were collected during either, the dives nor the dredges (see below), the nearest ever recovered gabbros and peridotites came from the Marie Celeste Fracture Zone, about 200 km north (Engel and Fisher, 1975). This observation further substantiates the inference of a "hot" and magmatically robust section of the CIR at 19°S deduced from the bathymetric and geophysical data;
- the high deposition rate of pelagic sediments results in rapid infilling of the structural lows. The undisturbed character of the sedimentary cover observed on the outer dives shows that active tectonics are focused on the inner valley floor and on the inner walls. Similarly, the absence of fresh lava on the outer dives suggests that active volcanism mostly occurs inside the inner valley floor;
- despite reported signs of possible hydrothermal plumes in the water column (Jean-Baptiste *et al.*, 1992), no active hydrothermal site has been observed, although evidence of pervasive hydrothermal circulation is widespread. This evidence includes the frequent occurrence of yellow-

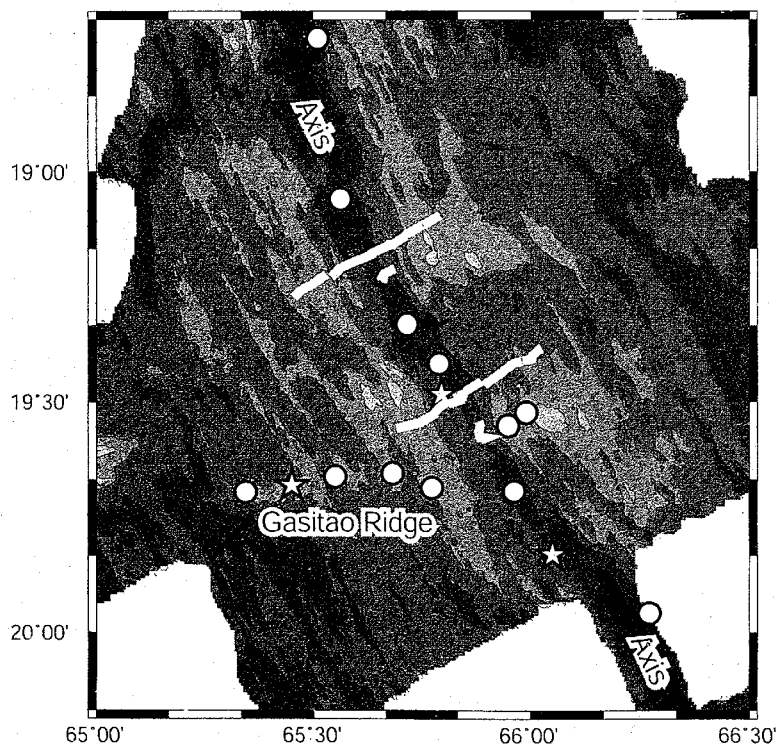


Figure 2. Dives of deep-sea submersible *Nautilie* carried out during the GIMNAUT cruise are shown by thick lines; they include the northern section (9 dives), the southern section (8 dives), and 3 isolated dives. Sites successfully dredged during the GIMNAUT cruise are marked by dots, other dredge sites by stars. Isobaths are plotted every 400 meters, between 2000 and 3600 m.

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ish and orange products of alteration (sulfurs ?) on young pillow lava and the diffusion of shimmering water out of en-echelon fissures seen at one location on Dive 20.

Other operations and preliminary results

Various operations were carried out during night time in order to complement the data collected in the same

area during the MAGOFOND 2 cruise of *R/V Marion Dufresne* in 1998 (Dymant *et al.*, 1999), including :

- the acquisition of deep tow magnetic profiles across the axial magnetic anomaly and the Brunhes-Matuyama boundary several hundred meters above the seafloor. Three such profiles had already been acquired during the MAGOFOND 2 cruise (Pouliquen *et al.*, *J. Geophys. Res.*,

in press). Two additional profiles were successfully obtained using deep tow magnetometers belonging to the Ocean Research Institute, Tokyo, and INSU/CNRS, France, respectively.

- the collection of rock samples during 12 dredge hauls (Fig. 2). Six sites were dredged along the CIR axis, adding to the 3 sites sampled previously (Engel and Fisher, 1975; Humler, pers. comm.). These and the samples collected by *Nautilie* provide a means to study the geochemical contamination of the ridge magmas by hotspot material at regional and local scales. Of the six dredge hauls devoted to a detailed investigation of the Gasitao Ridge, a small bathymetric feature which continues the Rodrigues Ridge up to the CIR axis (Dymant *et al.*, 1999), four were dredged on the ridge and two on the conjugate area on the Indian plate;

- and finally, the acquisition of multibeam bathymetry and imagery, surface magnetic and gravity data.

The multibeam bathymetric data collected with the Simrad EM 12 Dual system of *R/V L'Atalante* validate those collected during the MAGOFOND 2 cruise with the Thomson Marconi Sonar TSM5265 "Sea Falcon" system of *R/V Marion Dufresne*. The dense coverage of sea-surface potential field data allows the computation of gravity and magnetic anomaly grids, on which the study of deep-sea potential field data will rely. Initial analysis presented in Fig. 3 show the equivalent magnetization computed from the bathymetric and surface magnetic data assuming a 500 m-thick magnetic layer. Anomalies 1, J, 2 and 2 A (Brunhes normal chron, Jaramillo and Olduvai normal sub-chrons inside Matuyama reversed chron; and Gauss normal chron) are clearly identified. Secondary linear features are also occasionally seen and agree well with the tiny wiggles recognized by Pouliquen *et al.* (*J. Geophys. Res.*, in press) as geomagnetic features (for example, Cobb and Reunion events). Within the axial (Brunhes) anomaly, two to three such linear features flank the Central

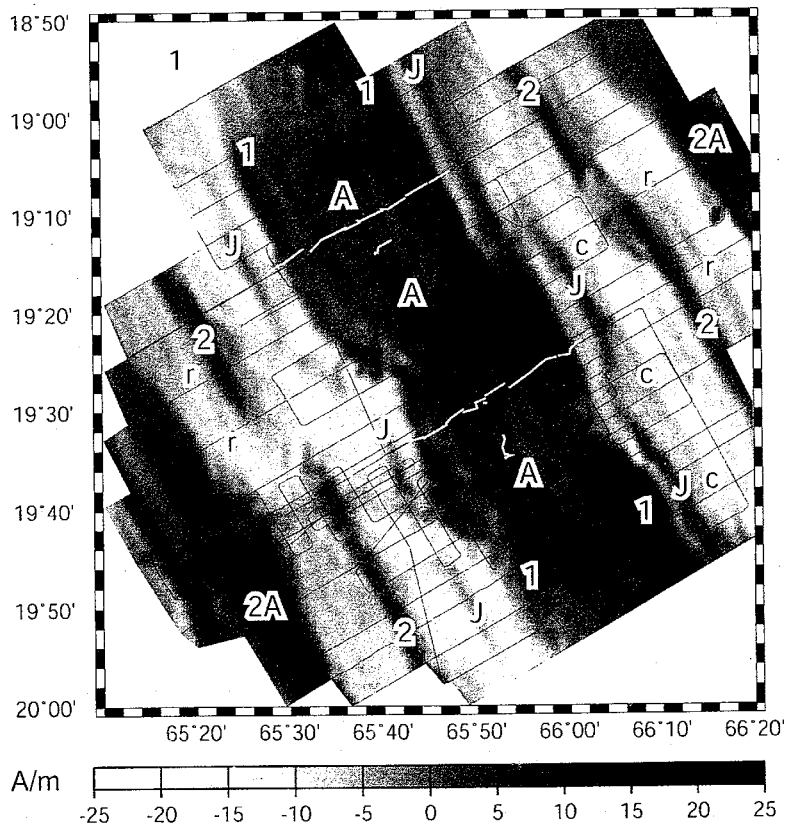


Figure 3. Equivalent magnetization computed from recent (*i.e.* 1995 and later) magnetic anomaly data in the GIMNAUT area. Original magnetic records have been reduced to the IGRF; an additional constant correction of several tens of nanoteslas has been applied to reduce the magnetic anomaly of each survey for systematic misfits at crossing points with the other surveys. Resulting magnetic anomaly data have been gridded using optimal Delauney triangulation and subsequently reduced to the pole. Equivalent magnetization was computed assuming a 500 m-thick magnetic layer and using a pass-band filter between 3 and 128 km. The 1, J, 2, 2A denote: anomaly 1 (*i.e.* the axial anomaly, which corresponds to the Brunhes chron), anomaly J (the Jaramillo sub-chron), anomaly 2 (the Olduvai sub-chron), and anomaly 2A (the Gauss chron), respectively. C marks the Central Anomaly Magnetic High. The r and c show clear occurrences of the Reunion and Cobb events, respectively. Also shown is the location of the sea-surface magnetic anomaly profiles (thin black lines) and *Nautilie* dive tracks (thicker white lines).

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Anomaly Magnetic High (CAMH) and will be analyzed together with the deep tow and submersible magnetic anomalies. The tremendous along-axis variations of the equivalent magnetization are associated with the faint, second-order, segmentation depicted by the bathymetry. Higher equivalent magnetization values correspond to segment ends and lower values to segment centres, as observed on other spreading centres.

Advantage was taken from transit periods to acquire bathymetry, imagery, magnetics and gravity, which will complete the data set acquired during the MAGOFOND 2 cruise. A small ridge was discovered northeast of Rodrigues Island during the first transit. This ridge trends N70°E, extends more than 36 km and towers 2000 m over the nearby seafloor (~ 3200 m deep). These characteristics make it very similar to the Three Magi and Gasitao Ridges (Dyment *et al.*, 1999) and suggest a common origin for these features.

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Exploration of the Carlsberg Ridge

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Surveys to explore the slow to medium spreading Carlsberg Ridge, which acts as a plate boundary between the Indian and African plates in the northern Arabian Sea, have been ongoing since 1996. A ~ 100 km long section of the Carlsberg ridge was surveyed with multi-beam bathymetry, gravity and magnetics and seabed sampling during the cruise on board *OR/V Sagar Kanya* (SK-114) in June-July 1996. In July-August 2000, a cruise (SK-154) was undertaken to augment the earlier data, and an area of ~ 17,000 km² was covered with the multi-beam swath bathymetry (MBS). Concurrent with MBS data, gravity and magnetics

were acquired. Geological sampling was carried out at selected locations based on MBS data. The recent exploration was carried out in two blocks separated by about 70 nautical miles.

Major transform faults or transform zones are absent in the region surveyed. However, the ridge axis showed a continuous and gradual shift in the trend. Along the axial valley, occurrence of axial lows of about 4700 m at regular intervals is a unique feature of Block 1 (Fig.1). These axial valley lows appear to influence the changes in the ridge axis trend. Another supportive evidence for this possible

interpretation is the presence of the topographic highs along the ridge flanks closer to these axial lows. Near the central part, gradual merging of the ridge axis into the ridge flanks and the absence of linear steep valley walls with a distinct topographic signature observed.

In the second block of the survey (Fig. 2), the axial valley was comparatively wider and showed gradual shallowing up of the axial valley floor to about 3600 m, from ~ 4000 m in Block 1. The contour map of Block 2, shows a non-transform ridge axis discontinuity which is flanked on the northern side by a topographic high