Large rotation of the Easter microplate as evidenced by oriented paleomagnetic samples from the ocean floor

J.P. Cogné a,*, J. Francheteau b, V. Courtillot a, Pito93 Scientific Team 1

a Laboratoire de Paléomagnétisme, Institut de Physique du Globe and Université Denis Diderot, 4 Place Jussieu, F-75252 Paris Cedex 05, France
b Département des Sciences de la Terre, Université de Bretagne Occidentale, 29287 Brest Cedex, France

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Abstract

One of the goals of the Pito93 cruise along the perimeter of the Easter microplate was to obtain oriented rock samples from the ocean floor for paleomagnetic study. Using a new orienting device, the Geocompass, 14 oriented blocks were obtained during 6 dives conducted using the Ifremer DSRV Nautil. Paleomagnetic analysis shows that 13 of these 14 blocks give consistent results in thermal and AF demagnetizations, and reveals a mean Characteristic Remanent Magnetization (ChRM) direction within each block, with both normal and reverse polarities. After elimination of data from 5 blocks situated outside the microplate, and one block which bears an anomalous direction, we have computed a mean ChRM direction at \( D_m = 49.0^\circ, I_m = -39.0^\circ \) (\( k = 10.2, \alpha_{95} = 19.8^\circ, n = 7 \)). Although the mean inclination is in agreement with the inclination of the recent dipole magnetic field (\( D = 0^\circ, I = -43^\circ \)), the average declination is significantly different from this direction, which we interpret as due to a bulk clockwise rotation of \( 48.5^\circ \pm 11^\circ \) (after the bivariate average) of the Easter microplate over the past 2–3 Ma. This value is in excellent agreement with previous estimates based on remote geophysical measurements and models.

1. Introduction

The Easter microplate is located on the East Pacific Rise, along the very fast spreading Pacific–Nazca boundary (Fig. 1). Numerous geophysical studies, including focal earthquake solutions, bathymetry, side-scan sonar imaging, Sea Beam and magnetic profiling, have shown that the microplate exists as a small rigid plate that is trapped and rapidly rotating between the diverging Pacific and Nazca plates. The east and west boundaries are two N–S trending, simultaneously active spreading centres, whereas the north and south boundaries are complex, transform-like fault zones with components of extension, compression and shear (e.g. [1–8]). This tectonic system has been approximated by a circular plate trapped between two major plates, the Nazca and Pacific [2,9,10] (Fig. 1c). Due to the overlapping spreading centres, a torque is exerted on the microplate circumference, forcing it to rotate about a vertical axis. In the case of the Easter microplate, this torque is dextral, causing clockwise
rotation. Both the ‘tectonic spreading fabric’ (normal fault scarps and abyssal hills formed near and parallel to the spreading centre; see Fig. 1) and the magnetic fabric fan westwards from the East Ridge, which is considered [6,7] as evidence for clockwise rotation since before at least chron 2A (3.88 Ma), the age of the earliest clearly recognizable magnetic anomaly in the microplate interior.

Because these interpretations are based on remote measurements, we made direct paleomagnetic sampling of oriented blocks from the Easter microplate during the Pito93 cruise (e.g. [11]), using the Nautilus submersible, with the goal of directly measuring the clockwise rotation of the microplate. To our knowledge, only one other such attempt has been reported recently [12].

2. Paleomagnetic sampling

Due to the lack of a deep-sea orientation device, up to now sampling oriented blocks of rock on the ocean floor has been impossible, and paleomagnetic work has been restricted to the study of magnetic properties and polarity sequences of cores drilled from the sea surface. In the present study, we have used a specially constructed compass, the Geocompass, devised by J.A. Karson from Duke University and R. Catanach at Woods Hole Oceanographic Institution. This apparatus, contained in a cubic aluminum frame, is made of a magnetic compass and 2 orthogonal vertical tilt meters, providing the measurement of three angles (Fig. 2a) which are recorded on a microcomputer every second, together with the
time of measurement. By holding the Geocompass against a planar outcrop with the arm of the submersible, these three angles allow one to compute the strike and dip of the plane. This apparatus was originally devised to measure orientations of dike margins, faults and fractures in ocean floor outcrops. We have used it to sample oriented blocks, allowing a complete paleomagnetic study to be performed.

The first paleomagnetic study of ocean floor samples, oriented using this device, has recently been published by Hurst et al. [12]. They describe an orientation procedure which consists in measuring the orientation of two lines drawn with the robot arm on a single planar surface, which allows determination of the orientation of this plane, and of a horizontal line fixed with respect to it.

During the Pito93 cruise, we established a different procedure to orient the rock samples: after having chosen a convenient block (that is in place, but fractured enough to be easily detached from the outcrop), two faces were measured (Fig. 2b); at the end of the dive, and with the help of video records, these two planes were identified and marked on each rock sample. Then a simple geometric construction on a stereonet (Fig. 2c) was used to determine the angle between the two faces (θ, Fig. 2), which could be checked on the block itself, and the angles between the intersection of the two planes and the horizontal within each plane (α and β, Fig. 2). Such horizontal lines were inscribed on each plane, which then allowed full use of the classical procedure of paleomagnetism (drilling oriented standard specimens normal to each plane). Based on the consistency of paleomagnetic results from specimens drilled normal to two independently oriented planes within each block, we could check for possible orientation problems arising, for example, from a faulty manipulation of the Geocompass, or large magnetic field declination, due to the strong magnetization of outcrops. This also provided a means of estimating orientation errors, as discussed below.

Due to technical difficulties and overall hard working conditions, inherent to sampling on the ocean bottom, only 14 oriented blocks were obtained during 6 dives (Fig. 1; Table 1): 2 blocks on the East side of the East Ridge (dive 02), 5 blocks around Pito Deep (dives 06 and 11), 3 blocks near the Terevaka transform fault (dives 17 and 18), and 4 blocks in the Orongo fault zone (dive 20). Depending on the size of the blocks, 2–6 cores were drilled per block (total 62 cores), giving 5–15 standard paleomagnetic specimens (25 mm in diameter, 22 mm long) per block, with the exception of block 20-05, the small size of which allowed only 2 specimens to be obtained.

3. Paleomagnetic analysis

All magnetic measurements and demagnetizations were performed in the magnetically shielded room of the Paleomagnetic Laboratory at the Institut de Physique du Globe de Paris, Université de Paris 7-Denis Diderot. Remanent magnetization was measured with a 3-component 2G cryogenic magnetometer. A total of 64 specimens were demagnetized, in
10–15 steps, by alternating field (AF) in a 3-coil 2G demagnetizer in fields up to 100 mT, and 24 specimens were thermally demagnetized within a zero-field laboratory-built furnace. Measurements of bulk susceptibility were made with a Bartington susceptibility meter. Demagnetization results are plotted as orthogonal vector diagrams \([13]\) and equal-area projections. Paleomagnetic directions or planes were determined using principal component analysis \([14]\) and block mean directions were determined using Fisher \([15]\), or McFadden and McElhinny \([16]\) statistics for combined directional data and remagnetization circles.

Natural Remanent Magnetization (NRM) intensities range from 1 to 5 A/m (Table 1), with the exception of blocks 06-06 and 20-05. The initial magnetic susceptibility varies between 15 and 7800 \(\times 10^{-5}\) in volumetric SI units. Variations in both NRM and susceptibility values do not show any clear relationship with the petrographic nature of the rocks, which may be due to the small number of blocks. However, these values are in the expected range for gabbros, dolerites and basalts (e.g. \([17,18,21]\)).

Typical demagnetization curves for both AF and thermal demagnetizations are shown in Fig. 3. Most specimens have a simple behaviour and show univectoral decay toward the origin of orthogonal plots in AF (e.g., 36b in Fig. 3) as well as in thermal demagnetization (e.g. 39b), sometimes after removal of a viscous component generally cleaned by 100°C. All thermally demagnetized specimens show a high temperature component (HTC), unblocked by 500–580°C, suggesting that magnetite is the carrier of the HTC. Superimposed on this, a medium temperature component (MTC) unblocks in the range 350–400°C in cores from the blocks 02-03, 11-04 and 17-07, and in the range 400–500°C in cores from the blocks 06-06, 06-10 and 18-06. These values suggest the presence of larger magnetite grains and/or of higher Ti content in titanomagnetites \([19,20]\). These conclusions are consistent with those of Sempéré et al. \([21]\) in their study of magnetic properties of dredged basalt samples from the Easter–Nazca propagating

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Table 1

<table>
<thead>
<tr>
<th>Block Type</th>
<th>Location</th>
<th>Lat (S)</th>
<th>Lon (W)</th>
<th>Depth (m)</th>
<th>NRM (A/m)</th>
<th>Susceptibility (10^{-5} SI)</th>
<th>ChRM Dm/Im</th>
<th>n</th>
<th>k</th>
<th>(\alpha_{95})</th>
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<tbody>
<tr>
<td>Dolerite 02-02</td>
<td>25°06' 112°05'</td>
<td>2578</td>
<td>5.4±1.7</td>
<td>455±278</td>
<td>272.1°/27.3°</td>
<td>4.2°</td>
<td>4.08±1.7</td>
<td>4.08±1.7</td>
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<tr>
<td>Dolerite 02-03</td>
<td>25°06' 112°05'</td>
<td>2578</td>
<td>7.4±0.5</td>
<td>977±178</td>
<td>280.7°/33.4°</td>
<td>5.12±1.7</td>
<td>5.12±1.7</td>
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<tr>
<td>Gabbro 06-06</td>
<td>23°00' 111°55'</td>
<td>4865</td>
<td>0.78±0.07</td>
<td>348±44</td>
<td>30.8°/60.2°</td>
<td>6.65±8.4°</td>
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<tr>
<td>Gabbro 06-06</td>
<td>23°59' 111°54'</td>
<td>3869</td>
<td>0.051±0.010</td>
<td>1141±63</td>
<td>103.0°/42.9°</td>
<td>7.67±7.9°</td>
<td>7.67±7.9°</td>
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<tr>
<td>Dolerite 06-10</td>
<td>22°58' 111°53'</td>
<td>3200</td>
<td>4.91±0.8</td>
<td>3281±209</td>
<td>185.8°/16.4°</td>
<td>4.91±0.8</td>
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<td>Dolerite 11-02</td>
<td>23°03' 112°08'</td>
<td>3050</td>
<td>1.9±1.2</td>
<td>152±5</td>
<td>55.9°/33.1°</td>
<td>5.15±5</td>
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<td>Basalt 11-04</td>
<td>23°04' 112°08'</td>
<td>2610</td>
<td>2.2±0.8</td>
<td>150±13</td>
<td>228.9°/53.4°</td>
<td>5.81±8.6°</td>
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<tr>
<td>Gabbro 17-07</td>
<td>24°15' 115°40'</td>
<td>2605</td>
<td>2.2±0.9</td>
<td>2150±874</td>
<td>29.9°/64.1°</td>
<td>7.56±8.8°</td>
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<td>Dolerite 18-06</td>
<td>24°13' 115°36'</td>
<td>3294</td>
<td>1.9±0.1</td>
<td>1028±53</td>
<td>97.2°/58.9°</td>
<td>7.59±7.9°</td>
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<td>Gabbro 18-08</td>
<td>24°13' 115°36'</td>
<td>3106</td>
<td>1.8±0.5</td>
<td>48±8</td>
<td>348.1°/76.9°</td>
<td>6.105±6.6°</td>
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<td>Dolerite 20-05</td>
<td>26°41' 114°20'</td>
<td>2720</td>
<td>0.026±0.002</td>
<td>15±3</td>
<td>(no result)</td>
<td>(no result)</td>
<td>(no result)</td>
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<tr>
<td>Dolerite 20-07</td>
<td>26°41' 114°20'</td>
<td>2631</td>
<td>1.4±0.1</td>
<td>395±135</td>
<td>216.4°/11.5°</td>
<td>8.40±8.8°</td>
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<tr>
<td>Dolerite 20-08</td>
<td>26°41' 114°20'</td>
<td>2488</td>
<td>1.2±0.5</td>
<td>7219±396</td>
<td>47.0°/17.0°</td>
<td>6.341±3.6°</td>
<td>6.341±3.6°</td>
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<tr>
<td>Dolerite 20-09</td>
<td>26°41' 114°20'</td>
<td>2488</td>
<td>1.7±0.4</td>
<td>7806±181</td>
<td>41.9°/25.5°</td>
<td>7.148±5.0°</td>
<td>7.148±5.0°</td>
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</table>

Lat = Latitude; Lon = Longitude; NRM = arithmetic mean of Natural Remanent Magnetization (NRM) measurements; n = number of measurements per block; Susceptibility = arithmetic mean of n measurements per block, in volumetric dimensionless SI units; ChRM = mean direction of Characteristic Remanent Magnetization directions determined after thermal and/or AF demagnetization, given as Dm = Declination, Im = Inclination; n, k, \(\alpha_{95}\) = Fisher parameters \([15]\).
rift. The two components (MTC and HTC) have the same direction in 20 out of the 24 thermally demagnetized specimens, as illustrated in Fig. 3, specimen 39b. A characteristic remanent magnetization direction (ChRM) was thus determined in each specimen in the whole range of AF or temperature, and the average ChRM computed using Fisher statistics [15]. Only results from block 20-05 had to be rejected. The 2 specimens from block 20-05 gave noisy and inconsistent results, probably because of their low magnetic content, as suggested by low NRM and susceptibility values (Table 1).

There is one exception to the simple behaviour just described, illustrated in Fig. 3, specimen 17a, from the block 06-06. In this block, which has a significantly lower NRM intensity (Table 1), the demagnetization paths are not linear and do not converge towards the origin, due to joint demagnetization of (at least) two separate components of magnetization. The HTC could be separated in only three thermally demagnetized specimens, whereas remagnetization great circles were determined on the remaining four specimens, demagnetized by AF. Only in this block had the average ChRM direction to be determined using McFadden and McElhinny statistics [16].

4. Analysis of paleomagnetic results

4.1. Within-block averages

The ChRM directions and their averages are shown for each dive and each block as stereonets in

Fig. 3. Typical examples of behaviour of Easter microplate samples in AF (upper row) and thermal (lower row) demagnetizations. Right: normalized magnetic intensity decay curves, left: orthogonal vector end-points projections (12); ○ = projection onto the horizontal plane; • = projection onto the vertical plane; steps are given in mT for AF demagnetization, in °C for thermal demagnetization.
Fig. 4 and in Table 1. The data are reasonably well clustered within each block. One may note, however, that within blocks 02-03, 06-10, 18-06 and 20-07, directions cluster in two separate groups, depending on the plane the cores were taken from. The angle between the two groups is of the order of 20°: this
value probably provides a good estimate of the maximum error in block orientation. We also underline that our \( \alpha_{95} \) areas are much larger than those of Hurst et al. [12], which we explain as being due to the different procedures in orienting the blocks; our procedure, consisting in orienting 2 faces provides two independently determined orientations of a block, allowing us to reject the possibility of large orientation errors, which are not discussed in [12].

Out of the 13 blocks, 9 show normal directions, with upward inclinations (open squares and circles, Fig. 4) and 4 have reverse directions with downward inclinations (filled squares and dots). Blocks 11-02 and 11-04 show both directions, with a low AF unblocking component, which is reverse in block 11-02, normal in block 11-04 (Fig. 3, specimen 24a). The overall distribution of block mean directions is shown in Fig. 5a. At first sight, this distribution may appear to be very scattered and certainly deserves discussion.

**Fig. 5. (a) Equal-area projection of mean ChRM directions from 13 blocks with their 95% confidence intervals. Large ellipses are the spherical shells of \( 2\sigma = 40^\circ \) around the normal (D = 0°, I = -43°) and reverse (D = 180°, I = 43°) dipole field directions (scatter expected from orientation errors and paleosecular variations; see text). (b) Number of data contained in the 2\( \sigma \) areas, as a function of the rotation \( \alpha \) of the center of the spherical shells of (a) from 0° to 360°. (c) Equal area projection of the 7 final mean ChRM directions and their Fisher [14] (open star with \( \alpha_{95} \) in light grey) and LeGoff [21] (open star with the ellipse of 95% confidence in dark grey) averages showing a rotation of 48° ± 11°. Same conventions as in Fig. 4.**
4.2. Theoretical versus observed dispersion

Before making any selection of data based on the tectonic settings of the blocks, we can test a first hypothesis which is: (1) the magnetization of the blocks is primary; (2) it has been acquired in a direction close to the average long-term axial dipole field direction \( (D = 0^\circ, I = -43^\circ) \), with some dispersion as discussed below; and (3) accounting for previous tectonic interpretations of the Easter microplate, magnetization of all the blocks has undergone some amount of clockwise rotation about a vertical axis.

We may estimate two main sources of dispersion around a possible common mean direction: (1) scatter due to errors in measuring magnetization, which are dominated by errors in block orientation; (2) dispersion arising from the scatter of virtual geomagnetic poles (VGP) due to paleo-secular variation (PSV, [22]). Obviously, there is a third source of dispersion, which is the component of rotation around horizontal axes due to block tilting near spreading centres (e.g., Hurst et al. [12]). This will be discussed later.

Let \( \sigma^2 \) be the variance about the average direction, \( \sigma_p^2 \) the variance due to errors in block orientations, and \( \sigma_v^2 \) the variance due to the VGP scatter. Assuming that the two sources of uncertainty are independent, we have \( \sigma = \sqrt{\sigma_p^2 + \sigma_v^2} \). Following the above discussion, we estimate \( \sigma_p \), as about 10°. VGP scatter is a function of paleo-latitude, and, according to the 'G model' of McFadden et al. [22], is about 15° for a latitude of 25°. This results in \( \Delta D = 20^\circ \) and \( \Delta I = 15^\circ \) at the sampling location. We thus estimate directional scatter due to PSV as \( \sigma_v = 17^\circ \).

With these values \( \sigma \approx 20^\circ \). This means that, if the observed scatter arises from these 2 sources, 95% of the data should lie in a cone with an aperture angle of \( 2\sigma = 40^\circ \) around their mean direction.

To test the above hypothesis, we constructed a window consisting of 2 spherical shells with a \( 40^\circ \) aperture around the expected normal and reverse dipole field directions \( (D = 0^\circ, I = -43^\circ \) and \( D = 180^\circ, I = 43^\circ \); Fig. 5a), and we scanned the sphere by rotating these shells about a vertical axis, from 0° to 360°, by 10° steps.

The result of this scan is illustrated in Fig. 5b, which displays the number of data falling in the 2\( \sigma = 40^\circ \) areas as a function of rotation angle. The figure clearly shows a maximum of 9 out of 13 data when the window is rotated clockwise by 40–60°. The corresponding cluster of magnetization directions is rather clear in Fig. 5a (almost no data in the second and fourth quadrants of the projection). Two small secondary submaxima in the curves of Fig. 5b are due to blocks 18-08, 02-02 and 02-03.

The magnetization of 18-08 is obviously anomalous as it has a very steep downward northerly direction (Table 1, Fig. 5a); this may arise from either a local tectonic rotation, sampling of a displaced outcrop, or erroneous orientation. As far as blocks 02-02 and 02-03 are concerned, we note that dive 02 is located to the east of the northward propagating East Rift and to the west of the nearby failing rift (Fig. 1). This places the samples in a sinistral zone of shear, which should result in a counter-clockwise rotation of the nearby crust [6,8,21]. This could explain the counter-clockwise rotation of magnetic directions from these two blocks.

Finally, although data from dive 06 match the above model, we note that: (1) this dive is situated on the northern flank of Pito Deep, and most likely pertains to the Nazca plate; and (2) data from this dive are very scattered (Figs. 4 and 5a), although the three outcrops sampled are situated a few hundred meters apart. Because these data appear to be suspect, we reject them from our paleomagnetic estimate of the Easter microplate rotation.

4.3. Paleomagnetic estimate of the Easter microplate rotation

The remaining 7 directions from dives 11, 17, 18 and 20 are shown in Fig. 5c, together with their averages. The Fisher mean [15] is \( D_m = 49.0^\circ, I_m = -39.0^\circ (k = 10.2, \alpha_{95} = 19.8^\circ) \). However, the distribution is obviously elongated, with a greater scatter in inclination than in declination. For this reason, we computed the average direction using the bivariate, orientation tensor-based, statistics of LeGoff [23]. This average direction (ellipse in Fig. 5c) is: \( D_m = 48.5^\circ, I_m = -38.0^\circ, kx = 40, ky = 6, \alpha_{95}x = 8.3^\circ, \alpha_{95}y = 20.1^\circ \). These two averages are not distinguishable, but declination is better constrained in the latter. Both are consistent with our original hypothesis that: (1) magnetization is primary; (2) its scatter
is dominated by secular variation of the magnetic field and orientation errors due to sampling; and (3) the population of direction has experienced a bulk clockwise rotation, which probably reflects the actual rotation of the Easter microplate. This provides an estimate of $48.5^\circ \pm 11^\circ$ for the rotation.

Finally, we note that, if we remove the effects of this bulk rotation, the distribution resembles the one of Hurst et al. [12], with a greater dispersion in inclination than in declination. This scatter appears to be most probably due to some block tilting around horizontal axes in the vicinity of spreading axis at the time of crust formation, as evidenced by Hurst et al. [12]. At the statistical level of significance, however, the deviations due to the effects of this horizontal component of rotation average around the dipole field inclination.

5. Conclusions

Using a new orienting device, the Geocompass, carried by the submersible *Nuutile*, we were able to collect oriented rock samples from the ocean floor, on the Easter microplate, during the Pito93 cruise, in November 1993, allowing a paleomagnetic study to be performed. Our sampling procedure, which consists in orienting two planar faces of each block, whenever possible, allowed us to check for large errors in orientation and to estimate orientation uncertainties at about $\pm 10^\circ$.

Fourteen oriented blocks were recovered during 6 dives. Thirteen of these 14 blocks give consistent results in both thermal and AF demagnetizations, allowing us to define a mean characteristic remanent magnetization direction within each block, with both normal and reverse polarities. The resulting ChRM distribution for all the blocks appears quite scattered.

An analysis of this scatter, taking into account paleo-secular variation, orientation uncertainties in sampling and location of the dives, leads to the conclusion that at least 7 of the 13 magnetization directions are consistent with the hypothesis that the ChRM is a primary magnetization and has been rotated clockwise by $48.5^\circ \pm 11^\circ$ since $2.5 \pm 0.5$ Ma. Of course, the number and location of sites only allows an estimate of an average rotation, and not its detailed distribution, as presented, for instance, by Naar and Hey [6].

We interpret this rotation as a net clockwise rotation of the whole Easter microplate around a vertical axis. The sense of this rotation is in agreement with the one predicted by the models of Engeln et al. [9] and Schouten et al. [10] and its amount is consistent with previous estimates based on the tectonic fabric of the microplate, and the pattern of its magnetic anomalies (e.g., see [3,5,6,8]). The rotation rate of the plate is difficult to evaluate, because of the lack of radiometric age control of our samples, but is approximately $23.5^\circ \pm 11^\circ$/Ma, consistent with published rotation rates for the Easter microplate.

Although better estimates could certainly have been obtained with a larger number of blocks from each dive (to evaluate orientation errors more accurately) and a larger number of dives, particularly in the central part of the microplate (to avoid effects due to nearby active tectonic boundaries), this study appears very encouraging in that it demonstrates the feasibility of underwater sampling of oriented blocks for use in paleomagnetic studies. Also, it provides the first direct underwater field evidence of large and fast microplate rotation.

Acknowledgements

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References


