From slow to ultra-slow: How does spreading rate affect seafloor roughness and crustal thickness?

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1) Table DR1.

Table DR1. Sources of multi-beam bathymetric data

<table>
<thead>
<tr>
<th>Cruise</th>
<th>Year</th>
<th>Research vessel</th>
<th>Multibeam system</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>RODRIGUES</td>
<td>1984</td>
<td>Jean Charcot</td>
<td>Seabeam</td>
<td>Munschcy and Schlich, 1990</td>
</tr>
<tr>
<td>RC2709</td>
<td>1986</td>
<td>Conrad</td>
<td>Seabeam</td>
<td>Dick et al., 1991</td>
</tr>
<tr>
<td>CAPSING</td>
<td>1993</td>
<td>L’Atalante</td>
<td>Simrad EM12D</td>
<td>Mendel et al., 1997; Patriat et al., 1997</td>
</tr>
<tr>
<td>GALLIENI</td>
<td>1995</td>
<td>L’Atalante</td>
<td>Simrad EM12D</td>
<td>Mendel et al., 2003; Sauter et al., 2001</td>
</tr>
<tr>
<td>FUJI - MD108</td>
<td>1997</td>
<td>Marion Dufresne</td>
<td>Thomson Seafalcon 11</td>
<td>Gomez et al., 2006; Sauter et al., 2002</td>
</tr>
<tr>
<td>INDOYO - YK98-07</td>
<td>1998</td>
<td>Yokosuka</td>
<td>Furuno HS10</td>
<td>Cannat et al., 2003; Fujimoto et al., 1999</td>
</tr>
<tr>
<td>YK98-08</td>
<td>1998</td>
<td>Yokosuka</td>
<td>Furuno HS10</td>
<td>Baines et al., 2007; Hosford et al., 2003</td>
</tr>
<tr>
<td>Kerimis – MD109</td>
<td>1998</td>
<td>Marion Dufresne</td>
<td>Thomson Seafalcon 11</td>
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<td>KR00-06</td>
<td>2000</td>
<td>Kairei</td>
<td>Seabeam 2100</td>
<td>Baines et al., 2007; Hosford et al., 2003</td>
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<tr>
<td>YK01-14</td>
<td>2001</td>
<td>Yokosuka</td>
<td>Seabeam 2100</td>
<td>Baines et al., 2007; Hosford et al., 2003</td>
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<td>SWIR 61-65 - MD135</td>
<td>2003</td>
<td>Marion Dufresne</td>
<td>Thomson Seafalcon 11</td>
<td>Cannat et al., 2006</td>
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<td>VANC10MV</td>
<td>2003</td>
<td>Melville</td>
<td>Simrad EM120</td>
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<td>Marion Dufresne</td>
<td>Thomson Seafalcon 11</td>
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<td>Pluriel – MD157</td>
<td>2006</td>
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<td>Kergueplac 3 – MD165</td>
<td>2008</td>
<td>Marion Dufresne</td>
<td>Thomson Seafalcon 11</td>
<td>NA</td>
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<tr>
<td>Geiseir – MD171</td>
<td>2009</td>
<td>Marion Dufresne</td>
<td>Thomson Seafalcon 11</td>
<td>NA</td>
</tr>
</tbody>
</table>

Note: US data are available at [http://www.marine-geo.org/](http://www.marine-geo.org/)
Japanese data are available at [http://www.jamstec.go.jp/cruisedata/e/](http://www.jamstec.go.jp/cruisedata/e/)
French data are available at [http://www.ifremer.fr/sismer/index_UK.htm](http://www.ifremer.fr/sismer/index_UK.htm)
2) **Seafloor roughness estimation**

The compiled bathymetric data were merged and gridded within their resolution limit at 0.15 km, which is sufficient to derive second-order statistical properties of abyssal hill morphology in ~80 km long (on average) polygonal areas with straight, parallel or sub-parallel sides aligned with spreading flow lines. We excluded areas with ages younger than C3An.y to avoid the relief associated with the axial valley and the rift mountains. We selected areas in the segment centers with well marked abyssal hills, excluding inside and outside corners as much as possible. We also avoid areas with detachment faults (Baines et al., 2003; Cannat et al., 2009; Cannat et al., 2008; Dick et al., 1991), smooth non-volcanic seafloor (Cannat et al., 2006) and oblique ridges and valleys occurring in non-transform discontinuities. Figure 1 shows examples of selected areas designated by boxes for seafloor roughness estimates.

3) **Mantle Bouguer Anomaly (MBA) calculation:**

We merged and gridded the free air gravity anomalies at 0.4 km. We obtain MBA values by removing the effect of a constant thickness (5 km), constant density (2700 kg/m³) crust from satellite derived free air anomaly data (Sandwell and Smith, 2009). GEBCO bathymetry (Fisher and Goodwillie, 1997) was used in MBA calculations to fill gaps in the shipboard bathymetry record and to avoid edge effects. Only areas with shipboard bathymetric coverage are considered in the interpretation of gravimetric data.

Gravity anomalies reflect the density structure of the crust and upper mantle but do not discriminate between crustal thickness variations and variations of the crust and upper mantle density structure. We therefore interpreted low MBA values as corresponding to thicker constant density model crust and/or to lighter mantle material, and high MBA values as corresponding to thinner constant density model crust and/or to denser upper mantle material. Because we excluded non-volcanic smooth seafloor areas where mantle-derived rocks are widely exposed in the seafloor (Cannat et al., 2006) from our analysis, we also assume that the crust in our selected areas is primarily volcanic and that density variations due to the presence of serpentinized mantle play a minor role.

We calculated residual MBA (RMBA) values along flow lines by removing the gravity effect of cooling of the plates with age using the magnetic anomalies identified by Patriat et al. (2008). The Phipps Morgan and Forsyth (1988) model which calculates mantle flow patterns based on ridge-transform geometry, was not used to determine the thermal correction because, unlike the age-based approach, this model requires constant spreading rate both along the ridge and over time, which is an assumption clearly violated here. The use of crustal age rather than passive flow modeling for the calculation of thermal correction, however, may lead to an underestimation of the thermal effects associated with long-offset transforms, because the effects of reduced upwelling and lateral asthenospheric flow were not considered. Georgen et al. (2001), however, have shown that both methods lead to very similar thermal corrections for the moderate-offset fracture zones in our study area (see their Figure 6).
4) The effect of sedimentation on seafloor roughness estimates

In order to accurately interpret the results of our multi-beam bathymetry analysis it is important to know the sediment thickness along the bathymetric profiles. The digital total-sediment-thickness National Geophysical Data Center (NGDC) database for the world's oceans and marginal seas (Divins, 2006) shows that sediments in our study area are <50m thick to the east of the Melville transform fault and <100m thick between the Gallieni transform system and the Melville transform fault. Such thin sediment does not significantly reduce the RMS amplitude of the bathymetry relative to the RMS amplitude of the basement (Downey et al., 2007; Goff and Tucholke, 1997). However, the NGDC database was gridded with a grid spacing of 5 arc-minutes by 5 arc-minutes and significant thickness variations may thus occur within each grid cell.

Fortunately, seismic data were collected during the Gallieni cruise (R/V L'Atalante October 1995) (Mendel et al., 2003; Sauter et al., 2001). They are available upon request at http://cats.u-strasbg.fr/. The survey area includes the deep and oblique domain between the Gallieni FZ and the Atlantis II FZ (Figure 2). Profiles were run parallel to the spreading direction (N03°E), spaced approximately 7 km apart, and reached C5n.o (Figure 3 and 4). A unique long profile reached the triple junction trace on the African plate (Figure 5). Six-channel seismic data have been collected using two Sodera GI guns with a 5-liter capacity (2x150 cubic inch). Ship speed during the survey was ~10 knots with a shot spacing of ~50 m. For the most part, seismic data show only one reflector corresponding to the seafloor. No sedimentary cover is observed in the segment centers up to C13y.o (Figure 4 and 5). The seismic data exhibit a lower reflector 0.0-0.25 s TWT (< 200m) beneath the seafloor only in small basins within the non-transform discontinuities (Figure 5), which we excluded from our analysis of seafloor roughness.

The sediment thickness was also estimated in the deep section of the SWIR east of the Melville transform fault during the SWIR 61-65 cruise (R/V Marion Dufresne, October 2003) using a Thomson 3.5 kHz sub-bottom profiler (Cannat, 2004; Cannat et al., 2006). These data show that the sediment cover is very thin (<130 m thick), even up to crustal ages >26 myr. Sediments are found only in the deepest basins (Cannat, 2004) which we excluded from our analysis of seafloor roughness. We thus conclude that the effect of sedimentation is negligible in the study area and that our seafloor roughness estimates are accurate estimates of the basement roughness.

References


Sauter, D., Cannat, M., and Mendel, V., 2008, Magnetization of 0-26.5 Ma seafloor at the ultraslow spreading Southwest Indian Ridge 61-67°E: Geochemistry, Geophysics, Geosystems, v. 9, p. Q04023

FIGURE CAPTIONS

Figure DR1: Bathymetric maps of selected boxes A. located between Gallieni and Novara FZ; B. located to the east of Melville FZ. Note the regularity of abyssal hills in A. and greater roughness in B. Black boxes: selected ultra-slow spread areas for roughness estimations; White boxes: selected slow spread areas for roughness estimations; dashed red line: SWIR axis; solid red lines: location of the gravity profiles shown in Figure 4. Magnetic anomaly identifications C6n.o (stars), C8n.o (triangles) and C13n.y (squares) are from Patriat et al. (2008) and Sauter et al. (2008), C5n.o hexagons are from Lemaux et al. (2002).

Figure DR2: Mantle Bouguer Anomaly map between the Gallieni FZ and 67°E with location map inset. Black boxes: selected ultra-slow spread areas for roughness estimations; White boxes: selected slow spread areas for roughness estimations. Dashed red line: SWIR axis; black lines: transform fault and fracture zone; solid red lines: location of the gravity profiles shown in Figure 3 of the main paper. Magnetic anomaly identifications C6n.o (stars), C8n.o (triangles) and C13n.y (squares) are from Patriat et al. (2008) and Sauter et al. (2008), C5n.o (hexagons) are from Lemaux et al. (2002). SWIR: Southwest Indian Ridge; SEIR: Southeast Indian Ridge; CIR: Central Indian Ridge; RTJ: Rodriguez Triple Junction.
**Figure DR3**: Bathymetric map of the SWIR between the Gallieni transform fault system and the Atlantis II transform (57°E). Maroon lines show the ship track. The thick dashed black line indicates the location of the seismic profiles shown in Figures 4 and 5. Magnetic anomaly identifications C6n.o (stars), C8n.o (triangles) and C13n.y (squares) are from Patriat et al. (2008) and Sauter et al. (2008), C5n.o (hexagons) are from Lemaux et al. (2002). Black boxes: selected ultra-slow spread areas for roughness estimations; White boxes: selected slow spread areas for roughness estimations. The dashed red line shows the SWIR axis.

**Figure DR4**: Seismic profile 71 across the SWIR within a segment center (see location in Figure 3). No sediment is observed.

**Figure 5**: Seismic profile 106 on the northern flank of the SWIR within a non-transform discontinuity and profile 107 along a segment center (see location in Figure 3). No sediment is observed in profile 107, but some small patches of sediments are found in the non-transform discontinuity. The sediment thickness does not exceed -0.25 s TWT (<200m) beneath the seafloor.
Figure DR2.
Profile 71

C5n.o

axial valley

time sTWT

shot

N

S

500 1000 1500 2000 2500 3000 3500