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*Geology* 2011;39:911-914
doi: 10.1130/G32028.1

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**Notes**

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ABSTRACT

We examine the relationship of seafloor roughness and gravity-derived crustal thickness to both spreading rate and inferred mantle temperature using statistical analysis of a multibeam bathymetry and gravity data compilation of the axis and flanks between 54°E and 67°E at the Southwest Indian Ridge (southwest Indian Ocean). Our findings indicate that root mean square values of abyssal hill heights increase from 220 ± 20 m to 300 ± 20 m along flow line corridors that transition a well-constrained full spreading rate change from slow (30 mm/yr) to ultra-slow (15 mm/yr). Mantle Bouguer gravity anomalies, however, indicate no significant change in inferred crustal thickness at the spreading rate transition. In the axis-parallel direction, roughness of both slow and ultra-slow seafloor increases from 54°E to 63°E while inferred crustal thickness and/or mantle temperature decrease. These findings have implications for the relationship between spreading rate and melt production: they suggest that mantle temperature at slow and ultra-slow ridges may play a more important role than spreading rate in determining seafloor morphology. The lack of evidence for significant crustal thinning accompanying a change from slow to ultra-slow spreading rate lends support to focused subaxial mantle upwelling models.

INTRODUCTION

Recent investigations of the Southwest Indian Ridge (SWIR) and Arctic ridges have revealed that the differences between ultra-slow and slow spreading ridges (full rate of <20 mm/yr and 20–55 mm/yr, respectively) are as great as those between slow and fast spreading ridges (Dick et al., 2003; Sauter and Cannat, 2010). The absence of volcanic activity on >100-km-long stretches of the ridge axis is one of the striking contrasts recently discovered between the SWIR and faster spreading ridges (Cannat et al., 2006; Dick et al., 2003; Sauter et al., 2004). It is also commonly inferred that both seafloor roughness and crustal thickness change dramatically for full spreading rates of <20 mm/yr (Menard, 1967; Reid and Jackson, 1981). Many of the differences between slow and ultra-slow spreading ridges are attributed to spreading rate, but how sure are we that spreading rate plays such an important role?

Some abyssal hill relief or seafloor roughness versus spreading rate curves indicate that the greatest increase in roughness occurs as spreading rate decreases from slow to ultra-slow (Ehlers and Jokat, 2009, Malinverno, 1991). However, Whittaker et al. (2008), in their global analysis, found no significant increase in gravity-derived seafloor roughness with slow to ultra-slow spreading rate decrease. There is considerable data scatter around any smooth relationship between roughness and spreading rate, as they are typically based on global compilations of data from several ridges (e.g., Ehlers and Jokat, 2009), including data from anomalously shallow or deep regions (e.g., at the SWIR; see Sauter et al., 2009). Factors other than spreading rate, such as mantle temperature, may affect the lithospheric strength and thus the roughness. Therefore, global compilations may not provide the best characterization of seafloor roughness variation related to a spreading rate change. Until the models are tested at slow and ultra-slow spreading ridges with extensive data coverage, how sure are we that this ultra-slow critical limit exists?

Although seismic crustal thickness shows little or no dependency on full spreading rate down to ~20 mm/yr, below this rate it is predicted to decrease rapidly (White et al., 2001). This prediction is based on subaxial mantle upwelling models in which enhanced conductive cooling below the ultra-slow critical limit results in thickening of the lithosphere and reduced upwelling velocities (Reid and Jackson, 1981). The vertical distance over which adiabatic melting occurs is in turn reduced, diminishing the amount of melt and thereby the volume of crust produced (White et al., 2001). However, the global-scale seismic crustal thickness studies and geochemical analyses that these models conceptualize are also based upon compilations of widely spaced data (White et al., 2001) and, therefore, may produce misleading results.

In this paper we make an unprecedented investigation into the role of spreading rate in determining seafloor character at slow versus ultra-slow spreading ridges by examining a well-constrained transition from slow (30 mm/yr) to ultra-slow (15 mm/yr) spreading at the SWIR. This transition occurred at magnetic anomaly C6C (ca. 24 Ma; Patriat et al., 2008) and produced only small local changes in plate boundary geometry (Baines et al., 2007). The key advance in our work is the ability to test the relationship of spreading rate with seafloor roughness and crustal thickness within individual flow line corridors as well as the relationship between seafloor roughness, crustal thickness, and inferred mantle temperature variation on the flanks parallel to the axis. We restrict our study to the 54°–67°E section of the SWIR (Fig. 1), which is the only part of the ridge with extensive data coverage, minimal sediment accumulation, and no hotspot influence. The eastern part of our study area is one of the deepest parts of the oceanic ridge system and is thus inferred to represent a colder, melt-poor end member of the ridge system (Cannat et al., 2008).

DATA AND METHODS

Bathymetry

We compiled multibeam bathymetric data from several French, Japanese, and U.S. cruises at the SWIR between 54°E and 67°E (see Table DR1 in the GSA Data Repository1). The stochastic modeling process of Goff and Jordan...
We obtained mantle Bouguer anomalies (MBA) by removing the effect of a constant thickness (5 km), constant density (2700 kg/m³) crust from free air anomaly data (see Fig. DR2). MBA lows correspond to thicker constant density model crust and/or to lighter crust or mantle material, and MBA highs correspond to thinner constant density model crust and/or to denser material. Mean values of the MBA were calculated within each of the boxes (Fig. 1) for the same time intervals (26–31 Ma and 8–13 Ma for slow and ultra-slow seafloor, respectively) to overcome variations in MBA due to age-related subsidence between the boxes. The effect of cooling of the plates with age was calculated using the magnetic anomalies identified by Patriat et al. (2008). The gravity effect of cooling of the plates with age was then removed from the MBA to obtain residual MBA (RMBA) values along flow lines.

RESULTS

Seafloor Roughness

We found that seafloor roughness in our study boxes varies not only along flow lines as spreading rate changes from slow to ultra-slow, but also with longitude parallel to the axis. We quantified the differences between slow and ultra-slow spread seafloor roughness properties by calculating the mean values of the parameter estimates weighted by the proportional error estimate within slow and ultra-slow populations (Goff, 1991). The mean RMS height of abyssal hills of ultra-slow spread seafloor (300 ± 20 m) is significantly larger than that of slow spread seafloor (220 ± 20 m). The angular difference (~12°) between the mean azimuths of the two populations is remarkably consistent with the change of spreading direction (~13°) obtained from kinematic analysis (Patriat et al., 2008). Figure 2A displays the variation of RMS abyssal hill height with longitude for the boxes selected for slow and ultra-slow spread seafloor. Although there is some overlap between the two populations, they are nevertheless distinct with,
for the most part, values for ultra-slow spread seafloor greater than for slow spread seafloor at a given longitude. West of the Atlantis II Fracture Zone, all but one box of ultra-slow spread seafloor show RMS heights of <200 m, the same or less than the RMS height estimated for slow spread seafloor (Fig. 2A). From the Atlantis II Fracture Zone to 63°E, both slow and ultra-slow populations display significant increase in RMS height (Fig. 2A). East of 63°E RMS heights for slow and ultra-slow populations decrease to values approaching the mean value for each of the respective populations.

**Mean Seafloor Depth and Gravity Signature**

Mean MBA and seafloor depth in our study boxes display the same regional trend as observed on axial data (Cannat et al., 1999; Georgen et al., 2001). The lowest MBA values for both slow and ultra-slow spreading crust are found east of the Atlantis II Fracture Zone and indicate thicker crust and/or lower densities. Between the Atlantis II and Melville Fracture Zones, mean MBA values and mean seafloor depth increase from west to east for slow and particularly for ultra-slow spread seafloor (Fig. 2), indicating an eastward thinning of the crust and/or an increase of densities. East of the Melville Fracture Zone, the mean MBA for ultra-slow spread seafloor decreases moderately eastward while the mean depth remains relatively constant.

Figure 3 displays RMBA variations along flow lines within three segments that maintained stable axial geometries since C13n.y (ca. 33 Ma). The three profiles are located west of the Atlantis II Fracture Zone, between the Atlantis II and Melville Fracture Zones and east of the Melville Fracture Zone, in three regional domains that have contrasting seafloor depth and MBA (Fig. 1; see the Data Repository). To the west of the Atlantis II Fracture Zone, there is a progressive decrease in RMBA as age decreases, with no visible variation associated with the change in spreading rate 24 Ma. Between the Atlantis II and Melville Fracture Zones, and east of the Melville Fracture Zone, the RMBA remains relatively constant on average over the entire investigated period (mean RMBA = 15 ± 6 mGal and 10 ± 5 mGal, respectively; Fig. 3). To the east of the Melville Fracture Zone, variations around this mean RMBA value have larger amplitudes and wavelengths for ultra-slow spread seafloor than for slow spread seafloor. This is in agreement with the more detailed analysis of RMBA performed in the eastern region (Cannat et al., 2006).

**DISCUSSION**

Seafloor roughness increases along flow lines on the flanks of the SWIR between 54°E and 67°E, where the full spreading rate decreased from 30 mm/yr to 15 mm/yr ca. 24 Ma, but we find no evidence for significant reduction in crustal thickness as a result of this spreading rate change. In fact, more negative RMBA values suggest that crustal thickness increases locally in ultra-slow spread seafloor (e.g., west of the Atlantis II Fracture Zone; Fig. 3A). The mean depth, seafloor roughness, and mean MBA within the ridge flank study boxes (Fig. 1) increase from west to east for both slow and ultra-slow spread seafloor between 54° and ~63°E (Fig. 2). These findings challenge some aspects of currently accepted models of seafloor spreading, in particular the relationships between spreading rate and melt production.

The SWIR is a unique example of an ultra-slow spreading ridge with little sediment accumulation and extensive survey coverage on axis and off axis, thus meeting the criteria for calculating stochastic estimates of seafloor roughness. Larger RMS abyssal hill height values (265-584 m) obtained from isolated seismic reflection profiles in the ultra-slow spreading Arctic Basin (Ehlers and Jokat, 2009) may not adequately account for regional morphology variability. RMS abyssal hill heights of slow spread SWIR seafloor (220 ± 20 m) are close to those estimated using the same method at the slow spread Mid-Atlantic Ridge (220–240 m) (Goff et al., 1995; Neumann and Forsyth, 1995). The thickness of the lithosphere near ridge axes increases with decreasing spreading rate (Huang and Solomon, 1988). Greater elastic strength at ultra-slow spreading ridges can support formation of larger topographic features. Accordingly, RMS abyssal hill height values are significantly larger for ultra-slow spread seafloor than for slow spread seafloor, suggesting that variation in roughness along flow lines at the SWIR is likely due to the change in spreading rate. This is further supported by the coherence of SWIR roughness estimates with global estimates and their relationship to spreading rate. However, the variability of seafloor roughness with longitude in our study area is also correlated, independent of spreading rate, with variations of mean depth and MBA (Fig. 2). This suggests that spreading rate is not the sole controlling factor of seafloor roughness.

These longitudinal variations of mean depth and MBA (Fig. 2) suggest that there is an axis-parallel, along-isochron variability in the density structure of the off-axis lithosphere, consistent with a gradual thinning of the low-density crustal layer from west to east, and/or with a colder mantle to the east. Such an eastward decrease of crustal thickness and/or mantle temperature was also inferred from gravity, seafloor depth, and basalt sodium content data collected along the SWIR axis in the same region (Cannat et al., 1999, 2008). Thinner crust in the easternmost part of the SWIR is confirmed by seismic data (Minshull et al., 2006; Muller et al., 1999). Colder mantle temperatures leading to lower degrees of mantle melting and a lesser melt production could affect the strength of the axial lithosphere (Behn and Ito, 2008; Shaw and Lin, 1996), and may play an important role in determining seafloor roughness. A similar influence of mantle temperature on seafloor roughness may be observed at the Southeast Indian Ridge between the Saint Paul and Amsterdam hotspot and the Australian-Antarctic discordance (e.g., Goff et al., 1997).

The trend of increasing seafloor roughness in our study boxes (Fig. 2) from the Atlantis II Fracture Zone to 63°E suggests that the strength of the axial lithosphere at the time this seafloor was formed increased with longitude. In the boxes west of the Atlantis II Fracture Zone and to the east of 63°E, we observe some variance in this trend that may be attributed to enhanced melt production (Figs. 1 and 2). Cold mantle temperature regimes may produce not only thicker lithosphere, but also narrower zones of mantle upwelling beneath the axis. This focusing of mantle upwelling may result in locally enhanced melt production (Bown and White, 1994; Cannat et al., 2008). Additional factors such as ridge obliquity and variations of melt supply with time at a given on-axis location may also affect the rheology of the axial lithosphere, explaining local variability of seafloor roughness.
The 15 mm/yr rate change from slow to ultra-slow spreading that occurred at the SWIR transitions the critical range of rates for which mantle rising beneath the ridge at corner flow velocities similar to the half-spreading rate would depart from adiabatic decompression (see White et al., 2001, their Fig. 24). Our observations show that there is no evidence for a thinner crust as spreading rates decrease from slow to ultra-slow in our study area. This is an argument in favor of a more complex relationship between spreading rate and melt production in the subaxial mantle. In the model of Bown and White (1994), which calls for corner flow with a spreading rate-dependent lithosphere wedge angle, mantle upwelling is focused, and therefore accelerated, beneath the ridge. While the half-spreading rate upwelling velocity corner flow model of mantle upwelling predicts a strong decrease of melt thickness (>2 km) as the full spreading rate decreases from 30 mm/yr to 15 mm/yr (e.g., Dick et al., 2003), the focused and accelerated mantle upwelling model predicts only a slight reduction (≈0.5 km) for the same spreading rate decrease (Bown and White, 1994). The absence of a significant reduction in crustal thickness as spreading rate decreases at the SWIR confirms that, as proposed by Cannat et al. (2008) and Sauter and Cannat (2010), the observations of compared gravity, seaﬂoor depth, and basalt chemistry, enhanced melt production due to focused and accelerated mantle upwelling may be a likely mechanism for the generation of magma at ultra-slow spreading ridges.

ACKNOWLEDGMENTS

We thank M. Maia, C. Hemond, and J. Dyment for providing unpublished data from the PLURIEL and GEISEIR cruises, and H. Kinoshita, S. Arai, T. Matsumoto, and H. Fujimoto, who agreed to provide YK08-08, KR00-06, YK04-14, and YK08-07 (Indomy) cruise data to us. We also thank X. Morin and B. Ollivier of IPEV (Institut Polaire Français), R. Iwase of JAMSTEC (Japan Agency for Marine-Earth Science and Technology), and B. Leclercq of Institut Français de Recherche pour l’Exploitation de la Mer), who helped us to gather the data, and two anonymous reviewers and Henry Dick for their comments.

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