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Thermo-mechanical control of axial topography of intra-transform spreading centers

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ABSTRACT

The Quebrada/Discovery/GoFar fracture zone region on the East Pacific Rise at ~4°S spreads at a "fast" half-rate of ~70 mm/yr and includes 8 intra-transform spreading centers with lengths ranging from 5 to 70 km. The longer spreading centers have uniform axial highs typically associated with fast spreading ridges. However, the Quebrada and GoFar fracture zones each contain 2–3 short spreading centers with axial depths as great as 4800 m, reminiscent of axial valleys at "slow" spreading centers such as the Mid-Atlantic ridge. Residual mantle Bouguer gravity anomalies (RMBA) indicate that these anomalously deep spreading centers are not isostatically compensated by thin crust. Instead, there must be a dynamic component to the axial topography similar to that invoked to explain the uncompensated topography at axial highs and median valleys for normal fast and slow spreading ridges. We show that a simple "rheological" parameter combining inferred crustal thickness and predicted depth of the 1000 °C isotherm correlates well with the axial depth at all spreading centers in the Quebrada/Discovery/GoFar region. Spreading centers with cold or thin crust tend to be deeper than those with hot and/or thick crust, with relief apparently amplified by stresses in the lithosphere. In addition, we note that the Quebrada and GoFar fracture zones are regions of normal to positive RMBA, contrary to a recent suggestion that negative RMBA and thicker crust is typical of fracture zones on fast spreading ridges.

1. Introduction

The Quebrada/Discovery/GoFar (QDG) intra-transform spreading region on the East Pacific Rise between 3° and 5°S and 102° to 107°W is an excellent locale to study ridge-transform dynamics and ridge morphology processes due to its fast half-spreading rate of ~70 mm/yr and its variety of spreading center lengths, morphologies, and ridge offsets (Searle, 1983). In this paper we present results from the April 2006 R/V *Knorr* cruise, where we recorded multibeam bathymetry, gravity, and magnetic measurements of the QDG study area with nearly 100% coverage over the active spreading region. There are 8 intra-transform spreading centers bounded by two normal ridges to the south (S1 in Fig. 1) and north (S10), with a total offset of the East Pacific Rise of ~400 km occurring over an along-axis distance of ~150 km. The two longer spreading centers, S4 and S6, partition the region from west to east into the GoFar, Discovery, and Quebrada fracture zones. We categorize the longest spreading center, S4, as an intra-transform center, because it is bounded on either end by transforms equal to or greater in length than the intervening spreading center. The remaining intra-transform spreading centers are much shorter and most feature deep axial valleys.

There is a well-documented correlation between spreading rates and axial morphology at mid-ocean ridges (Macdonald, 1982; Small and Sandwell, 1989). Slow spreading ridges such as the Mid-Atlantic Ridge with half-spreading rate <20 mm/yr typically have median valleys on the order of 1–2 km deep, with infrequent volcanism and rough and fractured topography. Mid-ocean ridges that spread at intermediate half-rates around 30–40 mm/yr, such as the South-East Indian Ridge and the southern East Pacific Rise, usually have poorly developed axial highs or a mild axial depression of around 50–200 m, with more frequent volcanism and increasingly uniform along-axis ridge topography. The QDG region and the northern East Pacific Rise spread at a fast rate, and their ridges have characteristically shallow axial highs, erupt frequently, and have relatively uniform along-axis topography with a triangle-shaped ridge crest or axial high. However, this typical fast spreading characteristic is not evident in the shorter, deeper spreading centers along the Quebrada and GoFar fracture zones, despite spreading at the same rate, implying an axial morphology dependent on additional factors.

If mantle flow is passively driven by motion of the plates, as spreading rate increases asthenospheric mantle upwells faster and has less time to lose heat conductively to the seafloor, so the lithosphere beneath a faster spreading ridge will be thinner and weaker and melt production may be greater. Several models based on this form of thermally controlled rheology are able to predict a transition from a dynamically maintained axial valley to no axial valley with increasing spreading rate, requiring either the development of a weak decoupling zone in the lower crust (Chen and Morgan, 1990a,b) or the absence of a strong mantle layer beneath the crust (Neumann and Forsyth, 1993).

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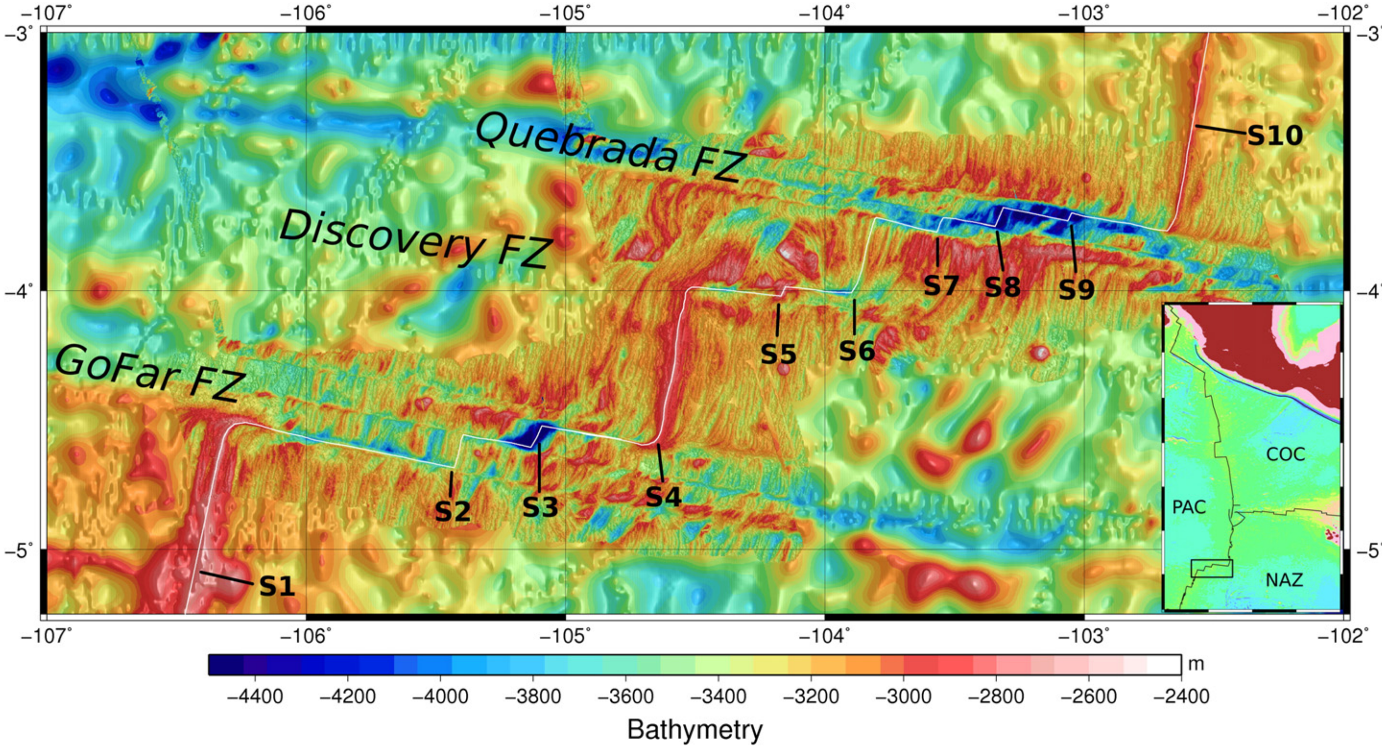

Fig. 1. Multibeam bathymetry acquired from the R/V *Knorr* of the Quebrada/Discovery/GoFar fracture zone region on the East Pacific Rise, with background predicted bathymetry based on satellite altimetry and pre-existing ship tracks (Ver. 10.1; Smith and Sandwell, 1997). Spreading centers labeled S1–10. White line denotes inferred plate boundary. Inset includes the Pacific, Cocos, and Nazca plates with plate boundaries in black and our study region given by the black rectangle.

Dynamic extensional stresses within the plate may also influence axial structure at fast spreading ridges, with axial highs resulting as a response to varying stress distributions from the upper to lower crust (Eberle and Forsyth, 1998) or bending stresses that develop from rapid hydrothermal cooling of the crust (Shah and Buck, 2003).

Axial topography at constant spreading rate also appears to be a function of magma supply, with uniform axial highs associated with thicker crust and shallow, steady-state magma chambers and discontinuous axial rift valleys corresponding to thinner crust with a less predictable melt delivery system. This effect can be seen in a broad sense at the intermediate spreading Galapagos ridge (Chen and Lin, 2004) as well as the slow spreading Reykjanes Ridge (Small, 1998), with thicker crust, shallower ridge axes, and absence of a median valley near the hotspots. The same principle also applies on a smaller, intra-ridge scale. At colder, slow spreading mid-ocean ridges mantle upwelling and melt delivery tends to focus towards the middle of the spreading center either from the effects of buoyant, diapiric upwelling or simply from slowing of passive upwelling towards the ends of spreading centers (Phipps Morgan and Forsyth, 1988; Magde et al., 1997), causing crust to thin (Tolstoy et al., 1993) and median valleys to deepen along-axis towards the transform faults. The effects of thinning crust on ridge topography are three-fold: isostatic deepening; a reduction of latent heat released in the crust as the magma solidifies; and the substitution of stronger upper mantle for relatively weak gabbroic lower crust. The latter two effects in combination with the slower upwelling control the thermo-mechanical properties of the lithosphere, resulting in dynamic deepening of the median valley towards fracture zones that is predictable if the crustal thickness is known (Neumann and Forsyth, 1993).

As with the fracture zone effect near the ends of slow spreading ridge segments, intra-transform spreading segments on fast spreading ridges are likely to be regions of lower temperature and reduced melt supply. These conditions are expected to lead to the absence of any steady-state magma chamber (Macdonald et al., 1991), an inference that is supported by the geochemistry of the basalts dredged within the transforms of the QDG region. The QDG intra-transform basalts have extremely variable degrees of enrichment in contrast to those dredged at normal ridges, indicating that these basalts are unaggregated and not well mixed in a steady-state magma chamber like those that lie beneath typical fast spreading ridge axes (Nagle et al., 2007). MgO concentrations are higher in the intra-transform basalts than on the longer spreading centers, indicating less differentiation. Together, these patterns are similar to the global patterns attributed to slower spreading rates and lower magma supply (Rubin and Sinton, 2007). In this paper we infer crustal thickness for the QDG area using our acquired gravity and bathymetry data and a three-dimensional mantle thermal model. We propose that the same factors that control intermediate and slow spreading ridge morphology, i.e., magma supply and shallow temperature structure, are also responsible for the axial crustal morphology observed at the fast spreading segments within the QDG fracture zones.

2. Data and mantle thermal model

Overall the data coverage and quality recovered was excellent, resulting in a bathymetry dataset gridded at 200 m. The few small between-track gaps were interpolated using via GMT 4.3.1's surface algorithm (Smith and Wessel, 1990) without significant loss. The *Knorr*'s gravimeter proved highly reliable with an average crossover error of 1.23 mgal. Gravity data collected during periods of ship turning or drifting were removed, and the remaining data were Eötvös corrected and filtered along-track to remove spurious values caused by the ship motion. Filtering was performed with a 250-second (corresponding to ~1 km at 8 knots) running average and then a 500-second Gaussian filter, in both instances replacing data outliers with the median value. This filtering does not attenuate wavelengths of geological interest. The zero level of the shipboard gravity data is adjusted to best match the free-air anomaly inferred from satellite altimetry (Sandwell and Smith, 2009; version 18.1) and then smoothly merged with the satellite field using GMT's surface algorithm. The resulting free-air anomaly is plotted in Fig. 2. The shipboard data helps constrain the amplitude of the shorter wavelength features better than the satellite data alone.