Earth and Planetary Science Letters 269 (2008) 259–270

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Thermally induced brittle deformation in oceanic lithosphere and the spacing of fracture zones

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ARTICLE INFO

Article history:
Received 22 June 2007
Received in revised form 24 January 2008
Accepted 8 February 2008
Available online 29 February 2008
Editor: C.P. Jaupart

Keywords:
oceanic lithosphere
fracture zone
thermal stress
brittle deformation

ABSTRACT

Brittle deformation of oceanic lithosphere due to thermal stress is explored with a numerical model, with an emphasis on the spacing of fracture zones. Brittle deformation is represented by localized plastic strain within a material having an elasto-visco-plastic rheology with strain softening. We show that crustal thickness, creep strength, and the rule governing plastic flow control the formation of cracks. The spacing of primary crack decreases with crustal thickness as long as it is smaller than a threshold value. Creep strength shifts the threshold such that crust with strong creep strength develops primary cracks regardless of crustal thicknesses, while only a thin crust can have primary cracks if its creep strength is low. For a thin crust, the spacing of primary cracks is inversely proportional to the creep strength, suggesting that creep strength might independently contribute to the degree of brittle deformation. Through finite versus zero dilatation in plastic strain, associated and non-associated flow rule results in nearly vertical and V-shaped cracks, respectively. Changes in the tectonic environment of a ridge system can be reflected in variation in crustal thickness, and thus related to brittle deformation. The fracture zone-free Reykjanes ridge is known to have a uniformly thick crust. The Australian-Antarctic Discordance has multiple fracture zones and thin crust. These syntheses are consistent with enhanced brittle deformation of oceanic lithosphere when the crust is thin and *vice versa*.

1. Introduction

The length of the mid-ocean ridge segments varies substantially among spreading centers and is correlated with several tectonic factors, including a positive correlation with spreading rate. The first order segments, bounded by transform faults (first order discontinuities), have an average length of 600±300 km along fast (>6 cm/yr) spreading ridges and 400±200 km for slow (<6 cm/yr) spreading ridges (MacDonald et al., 1991). Sandwell (1986) suggested that the length of the first order segments varies linearly with spreading rates. Although valid at the first order scale, such linear correlations are not supported at every level of the hierarchy. For example, the magmatic segments of slow to intermediate spreading ridges were shown to be 52.5 km long on average, independent of spreading rates (Briais and Rabinowicz, 2002).

Segment lengths are also apparently associated with regional variations in crustal thickness, creep strength, and mantle temperature. For instance, the Reykjanes ridge above the Iceland hot spot is known to have a uniform and much thicker crust for its spreading rate (Bunch and Kennett, 1980; Murton and Parson, 1993; Smallwood and White, 1998). This hot spot-affected ridge has been shown to exhibit signatures of wet mantle source for basaltic melt (Nichols et al., 2002). The water in crustal and mantle minerals has a strong weakening effect on creep strength although the preferential partitioning of water into melt phases complicates this straightforward relation (e.g., Karato, 1986; Hirth and Kohlstedt, 1996). In contrast, the Australian-Antarctic Discordance (AAD) has a highly rugged seafloor indicating increased fracturing (Hayes and Conolly, 1972; Weissel and Hayes, 1974) as well as anomalously thinner crust in comparison with other parts of the Southeast Indian Ridge (SEIR) (Tolstoy et al., 1995; Okino et al., 2004). Such regional features were attributed to colder mantle beneath the AAD (Weissel and Hayes, 1974), a hypothesis that was later supported by the systematics of major elements of basalt along the SEIR (Klein et al., 1991). These two regions, the Reykjanes ridge and the AAD, respectively exhibit reduced and enhanced segmentations at both the 1st and 2nd order compared with the other parts of the respective ridge systems. The degree of fracturing in those regions is substantially different in the profiles of free-air gravity anomaly (Fig. 1). The profile for the Reykjanes ridge (A–A') is smooth over the segment closer to Iceland and becomes rugged towards the southern end. The profile B–B' along the SEIR shows strong high frequency changes in depth and free-air gravity associated with the fracture zones over the AAD and with abrupt transition to a smooth segment east of the AAD.

A magma supply model has been proposed to explain the fundamentally different characteristics between slow- and fast-spreading centers, as well as axial morphology of a single ridge segment.

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0012-821X/$ – see front matter
doi:10.1016/j.epsl.2008.02.025

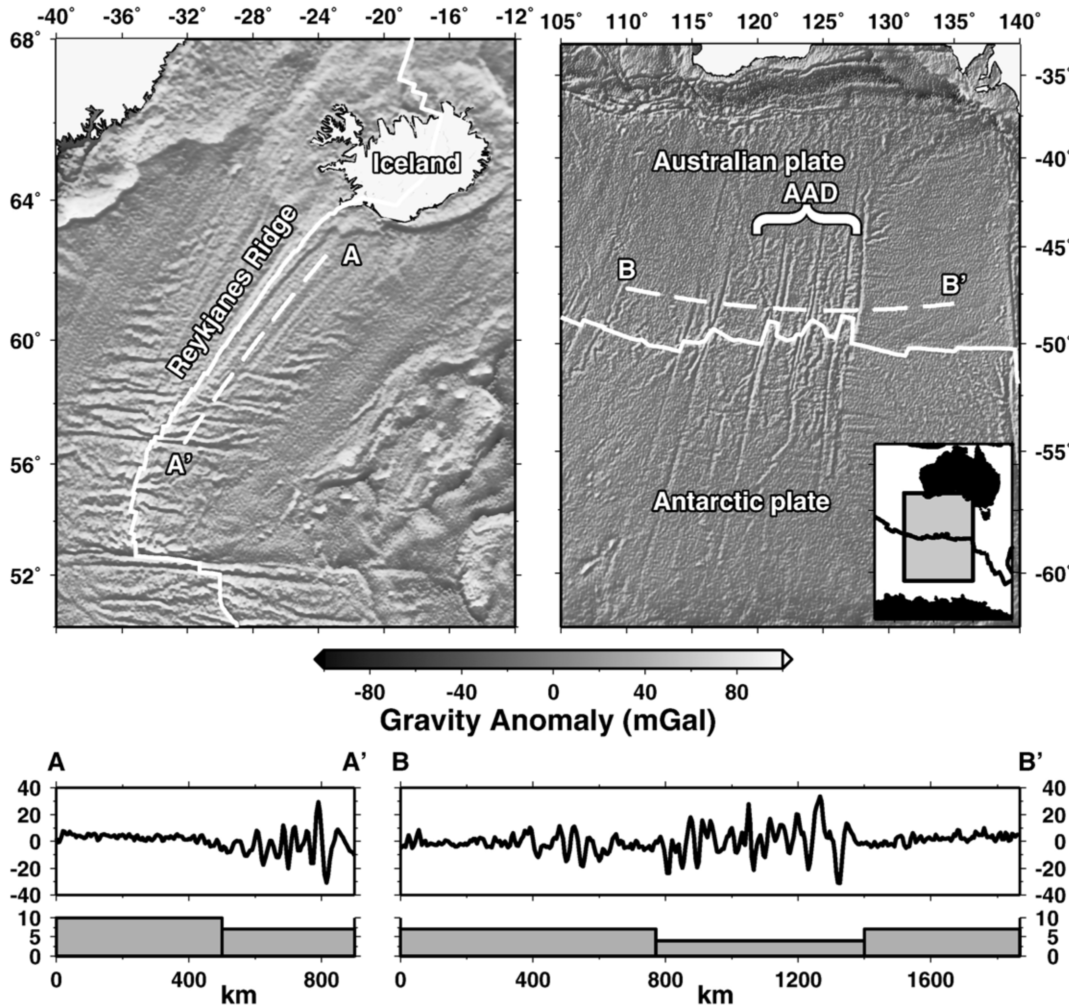

Fig. 1. Gravity anomaly maps derived from satellite altimetry of the Reykjanes ridge and the Australian-Antarctic Discordance (Sandwell and Smith, 1997). Thick white lines track the plate boundary (Bird, 2003). Each map is illuminated from the azimuths of 0° and 300°, respectively, so that the ridge-normal structures look prominent. Free-air gravity (in mGal) with mean removed (bottom panels) show the profiles (A–A' and B–B') with simplified variation of crustal thickness in km (lower plots). See text for crustal thickness references.

According to this model, the variable amount of available magma at spreading centers and its along-ridge transport are responsible for along-ridge variations in axial bathymetry and associated geophysical and geochemical observations (MacDonald et al., 1991; MacDonald, 1998). Relating mantle dynamics to the conceptual magma supply model, calculations of mantle flow beneath slow spreading centers exhibit 3-D patterns that are segmented along the axis (Parmentier and Phipps Morgan, 1990; Lin and Phipps Morgan, 1992; Barnouin-Jha et al., 1997; Madge and Sparks, 1997). A problem with such flow models is that the wavelengths of the segmented mantle upwelling are larger (150 km) than the observed average second order segment length (~50 km) (Barnouin-Jha et al., 1997). However, when the effect of melt extraction on the viscosity of the magma residual was taken into account, a much shorter wavelength of segmented flow (as short as 70 km) was achieved (Choblet and Parmentier, 2001). Related to the magma supply model, ridge migration with respect to a hot spot reference frame was suggested to cause asymmetric mantle upwelling and melt production (Carbotte et al., 2004). This model provides an explanation for the observation that the majority of "leading" segments (that is, those that step in the same direction as ridge migration direction) are magmatically more robust.

Although the magma supply model is consistent with a range of observations, the model has yet to be linked with the brittle manifestation of mid-ocean ridge segmentation. Thermal stress due to the cooling of oceanic lithosphere is one possible driving force responsible for brittle ridge segmentation among many others (cf. Kastens, 1987). Using an order of magnitude argument, Collette (1974) suggested that thermal stress associated with the cooling of oceanic lithosphere should exceed its strength. By computing the bending moment of a semi-infinite thin elastic plate experiencing top-down cooling, it was suggested that segment length should be determined such that a plate can release thermal stress by bending (Turcotte, 1974). Expanding on this theory, Sandwell (1986) showed that ridge-bounding first order discontinuities can release thermal stress effectively when their spacing is proportional to spreading rate. Decomposing thermal stress into contraction and bending components, Haxby and Parmentier (1988) speculated that thermal bending stress, not contraction, would govern the spacing of transform faults because the magnitude of thermal contraction stress was independent of the ridge segment length. These studies, however, provide only an upper bound or indirect estimate of the fracture zone spacing. Sandwell and Fialko (2004) focused on the optimal spacing between thermal cracks, which minimizes stored elastic energy in a bending plate. It is notable that the spacing is not given *a priori* but is determined by the principle of minimum elastic energy.

A theory of thermal cracks provides useful insight into the spacing of ridge discontinuities if we assume that ridge segmentation occurs due to thermal stress. The stress distribution as a function of distance from a two-dimensional crack has been analyzed by Lachenbruch (1962). In a thermally contracting elastic half space, stresses are assumed to be released on the wall of a vertical crack. At greater