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Magmatic controls on axial relief and faulting at mid-ocean ridges

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A B S T R A C T

Previous models do not simultaneously reproduce the observed range of axial relief and fault patterns at plate spreading centers. We suggest that this failure is due to the approximation that magmatic dikes open continuously rather than in discrete events. During short – lived events, dikes open not only in the strong axial lithosphere but also some distance into the underlying weaker asthenosphere. Axial valley relief affects the partitioning of magma between the lithosphere and asthenosphere during diking events. The deeper the valley, the more magma goes into lithospheric dikes in each event and so the greater the average opening rate of those dikes. The long-term rate of lithospheric dike opening controls faulting rate and axial depth. The feedback between axial valley depth D and lithospheric dike opening rate allows us to analytically relate steady-state values of D to lithospheric thickness H_L and crustal thickness H_C. A two-dimensional model numerical model with a fixed axial lithospheric structure illustrates the analytic model implications for axial faulting. The predictions of this new model are broadly consistent with global and segment-scale trends of axial depth and fault patterns with H_L and H_C.

1. Introduction

Mid-ocean ridges are the main places where magma exits the Earth's interior and new oceanic lithosphere is created and faulted. Thus, understanding the processes responsible for major spreading center features should give insight into the solid and fluid mechanics affecting other geologic systems such as continental rifts. The across-axis topographic shape of ridges show systematic variations with spreading rate (Macdonald, 1982; Small, 1998). Fast spreading centers (plate separation rates >8 cm/yr) are characterized by up axial high with up to 500-m of relief, while slow spreading ridges (plate separation rates <4 cm/yr) feature valleys as deep as 2 km (Fig. 1). Extensional faults exist at all ridges but there is a general increase in fault offset with decreasing spreading rate (Cannat et al., 2006; Carbotte and Macdonald, 1994; Small, 1998; Tucholke et al., 1998). The fault patterns show several different modes (Cannat et al., 2006; Carbotte and Macdonald, 1994) with a clear relation between magma input and fault mode (Buck et al., 2005; Tucholke et al., 2008).

In this paper we first describe previous spreading center models that fail to explain both axial relief and faulting pattern observations. We argue that to explain these observations requires consideration of the discrete nature of short-lived (i.e. hours to days) dike opening events at the axis of spreading. To do this, we need to parameterize the effect of individual dike events in a way that enables estimation of the effect of many such events on the long-term development of spreading center relief and faulting patterns. We build on previous studies of dike opening (Pollard, 1976; Qin and Buck, 2008; Weertman, 1971) to derive analytic relations between axial lithospheric thickness, the driving stress opening a dike and the distance of penetration of a dike into the asthenosphere. This analysis shows that the deeper the axial valley, the less magma goes into dikes opening into the asthenosphere. The magma intruded into the asthenosphere cools slowly to form gabbro and is not available to accommodate lithospheric plate separation.

Averaging over many dike events, we calculate the long-term flux of magma into the lithospheric part of dikes. We show that this lithospheric dike flux increases with axial depth, suggesting a way that magma supply could directly control axial depth. As long as the lithospheric dike opens at less than the plate spreading rate, then fault slip deepens the axial valley. If the valley gets deep enough that the dikes open as fast as the plates spread, then the valley stops deepening.

Numerical simulations of plate spreading are developed using these new analytic dike-opening relations to show that magma supply can control axial relief and affect near-ridge faulting. Assuming dikes supply all the magma to build the oceanic crust, we

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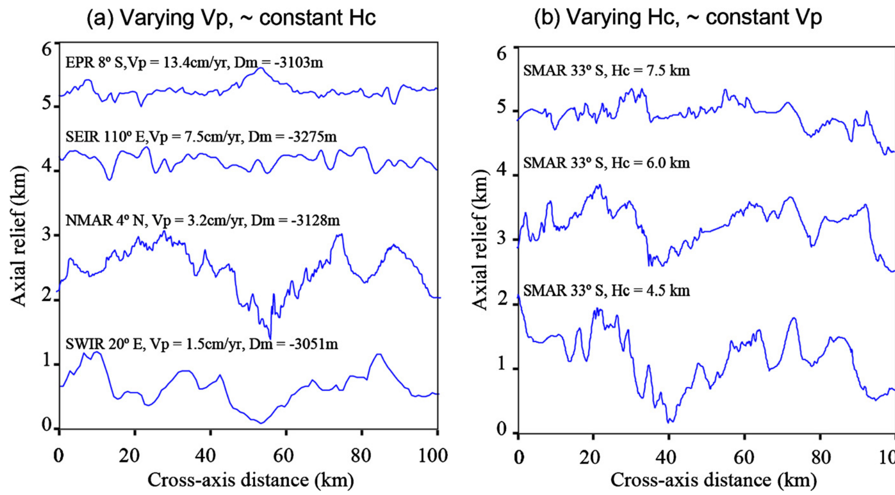

Fig. 1. Bathymetric profiles showing axial relief for different values of (a) spreading rate and (b) crustal thickness. V_P is full spreading rate; H_C, crustal thickness; *Dm* is mean depth within 40 km of the spreading axis defined by Small (1998) and should depend primarily on crustal thickness. EPR is the East Pacific Rise; SEIR, Southeast Indian Ridge; NMAR, Northern Mid-Atlantic Ridge; SWIR, Southwest Indian Ridge; SMAR, Southern Mid-Atlantic Ridge. Data from multibeam bathymetry are available at http://www.geomapapp.org/. Crustal thicknesses for different cross-sections of the 33°S segment of the SMAR are based on Tolstoy et al. (1993).

analytically describe how steady-state axial depth depends on axial lithospheric thickness and crustal thickness. Finally, we discuss how axial valley relief can be maintained by flexural stresses in the lithosphere when magma controls the axial valley depth and faulting does not accommodate plate spreading.

2. Previous models for spreading center relief and faulting

Global compilations show that axial relief depends on both spreading rate and crustal thickness (Small, 1998) (also see Fig. 1). Axial highs are generally thought to result from buoyantly support provided by low-density, possibly partially molten material under the spreading center (Buck, 2001; Eberle et al., 1998). The generation of axial valleys at spreading centers is more controversial. The two earliest ideas about steady-state axial valleys relate either viscous flow or tectonic faulting. The viscous flow idea is that flow of viscous asthenosphere into a narrow slot between two lithospheric plates could produce a valley with flanking highs (Sleep, 1969). A difficulty with this model is that viscous stresses and related valley depth should scale with plate separation velocity; predicting the deepest valley for the fastest plates, contrary to what is seen.

The tectonic control of axial valley formation was proposed by Tapponier and Francheteau (1978) who suggested that the faulting of the brittle axial lithosphere should produce a valley. Offset of normal faults dipping toward the spreading axis should deepen a valley, but they did not specify what would limit the valley depth. Phipps Morgan et al. (1987) used simple mechanical arguments to suggest that the depth of a tectonically generated valley scales with the thickness of axial lithosphere.

Several observations and recent models do not fit the view that axial valley depth scales simply with axial lithospheric thickness. At spreading centers with very thick crust and no axial valley, like Iceland and Afar, seismicity extends to nearly 10 km depth at the spreading axis (Ayele et al., 2009; Einarsson and Brandsdottir, 1980). Such thick brittle lithosphere would support a deep valley according to the tectonic model. Numerical models that self-consistently treat the mechanics of faulting show that tectonic extension of lithosphere as thin as that inferred for fast spreading ridges should result in moderately deep axial valleys (Qin and Buck, 2005).

Gradual changes in axial valley depth along some slow spreading segments do not clearly correlate with changes in axial lithospheric thickness. For example, a seismic refraction study along the 33°S latitude segment on the Mid-Atlantic Ridge shows crustal thickness differences of a factor of two (Tolstoy et al., 1993) (Fig. 8). Most of the variation occurs in the seismically fast crustal layer 3, thought to be composed of gabbros. Layer 2 is thought to primarily consist of dikes formed in the cold, brittle crust. If this is correct then the uniform thickness of Layer 2 implies that axial lithospheric thickness is nearly constant along this segment. As shown in Fig. 1 there is almost no axial valley near the segment center while the valley relief is nearly 2 km at the segment end. It appears that the reduced magma supplies to the segment ends, not thicker lithosphere, results in a deeper valley there.

Chen and Morgan (1990) were the first to incorporate magmatic dike intrusion into a spreading center thermo-mechanical model. In their model, magma was injected as a dike opening at a rate equal to the spreading rate from the surface down to the base of the crust. They found that a valley only forms when the axial lithospheric thickness H_L is greater than the crustal thickness H_C. This is consistent with work suggesting that magma-filled dikes open at lower stress differences that needed for tectonic faulting (Rubin, 1992; Rubin and Pollard, 1988). The Chen and Morgan (1990) model lithospheric thickness and valley relief increase as spreading rate decreases, consistent with the observed trend. However, Poliakov and Buck (1998) found that the constant dike height model produces no faulting in a model that allows for strain localization. They also noted that this dike geometry resulted in a non-physical stress singularity at the base of the dike.

In a numerical model that assumes dikes open to the base of the axial lithosphere, Buck et al. (2005) reproduced the observed range of spreading center faulting. Their model fault pattern depends on the ratio M of the rate of dike widening to the rate of plate spreading. For M close to 0.5, large-offset faults develop on one side of the axis, similar to the detachment faults found along slow-spreading ridges (Cann et al., 1997; Cannat et al., 2006; Tucholke et al., 1998). For M between ∼0.6 and 0.99 a series of nearly evenly spaced, moderate offset faults form in sequence, while for M between 0 and ∼0.4 a more chaotic pattern of fairly large offset faults prevails (Olive et al., 2010; Tucholke et al., 2008). For $M = 1$ the model produces an axial high with a height that depends on the density structure at the axis compared to that off-axis. However, for all values of M less than 1 the axial valley depth is independent of M and equals the depth predicted for purely tectonic extension (Qin and Buck, 2005).