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Constraints on dynamic topography from asymmetric subsidence of the mid-ocean ridges

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ABSTRACT

Stresses from mantle convection deflect Earth's surface vertically, producing dynamic topography that is important for continental dynamics and sea-level change but difficult to observe due to overprinting by isostatic topography. For long wavelengths ($\sim 10^4$ km), the amplitude of dynamic topography is particularly uncertain, with mantle flow models typically suggesting larger amplitudes (>1000 m) than direct observations. Here we develop a new constraint on the amplitude of long-wavelength dynamic topography by examining asymmetries in seafloor bathymetry across mid-ocean ridges. We compare bathymetric profiles across the Mid-Atlantic Ridge (MAR) and the East Pacific Rise (EPR) and we find that the South American flank of both ridges subsides faster than its opposing flank. This pattern is consistent with dynamic subsidence across South America, supported by downwelling in the lower mantle. To constrain the amplitude of dynamic topography, we compare bathymetric profiles across both ridges after correcting bathymetry for several different models of dynamic topography with varying amplitudes and spatial patterns. We find that long-wavelength dynamic topography with an amplitude of only ~500 m explains the observed asymmetry of the MAR. A similar model can explain EPR asymmetry but is complicated by additional asymmetrical topography associated with tectonic, crustal thickness, and/or asthenospheric temperature asymmetries across the EPR. After removing 500 m of dynamic topography, both the MAR and EPR exhibit a slower seafloor subsidence rate ($\sim$280–290 m/Myr$^{1/2}$) than previously reported. Our finding of only ~500 m of long-wavelength dynamic topography may indicate the importance of thermochemical convection and/or large viscosity variations for lower mantle dynamics.

1. Introduction

Convective flow in the mantle supports deflections of Earth's solid surface known as dynamic topography (e.g., Hager et al., 1985). Changes in this dynamic topography, which result from the time-dependence of mantle flow, have been identified as exerting important controls on sea level change (e.g., Conrad and Husson, 2009; Spasojevic and Gurnis, 2012) and continental dynamics (e.g., Liu, 2015) over timescales of millions of years. However, our understanding of the influence of dynamic topography is complicated by significant uncertainties over its amplitude. In particular, constraints on the long wavelength ($\sim 10^4$ km in width) components of dynamic topography range from a few hundred meters based on observational studies (e.g., Hoggard et al., 2016, 2017; Molnar et al., 2015) to upwards of one kilometer from mantle flow models (e.g., Conrad and Husson, 2009; Flament et al., 2013; Hager et al., 1985; Spasojevic and Gurnis, 2012). To constrain this uncertainty, we look for the signature of dynamic topography within bathymetric observations of seafloor subsidence away from mid-ocean ridges (e.g., Zhong et al., 2007).

Numerical mantle flow models predict vertical stresses that support dynamic topography at the Earth's surface. Models based on tomographic constraints on mantle density heterogeneity depend on the conversion factor $R = \delta \ln(\rho)/\delta \ln(v_s)$, which translates a tomographically-constrained seismic velocity anomaly into a mantle density anomaly. Typical estimates of R range from 0.15 to 0.4, with uncertainty associated with the relationships between the thermal expansion coefficient, temperature, density, pressure, and composition (e.g., Gurnis et al., 2000; Karato and Karki, 2001). Previous studies have utilized a nearly constant value of R (e.g., Conrad and Husson, 2009; Steinberger, 2016), or employed radial (e.g., Cammarano et al., 2003) or lateral viscosity variations in the lower mantle (e.g., Moulik and Ekström, 2016;

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Simmons et al., 2010). In particular, the large low-shear-velocity provinces (LLSVPs) in the lowermost mantle have been attributed to thermal effects, compositionally distinct materials, or a mix of factors (Deschamps et al., 2015; McNamara et al., 2010), all of which imply different distributions of mantle density heterogeneity (Bower et al., 2013; Moulik and Ekström, 2016; Simmons et al., 2010). This diversity of models for the mantle's internal heterogeneity leads to a range of different predictions for the amplitude of the associated dynamic topography (Liu and Zhong, 2016).

Observational constraints on the amplitude and pattern of dynamic topography could potentially help to resolve these uncertainties, and thus place new constraints on mantle processes. However, dynamic topography is difficult to observe directly because it is obscured by larger-amplitude isostatic topography associated with crustal density variations. One approach for detecting the component of topography that is dynamically supported is to use free-air gravity anomalies (Hoggard et al., 2016, 2017), which should be zero for isostatically-supported topography. However, the admittance, which converts free-air gravity anomalies to dynamic topography, is uncertain at long wavelengths, and may range from near zero or even negative values (Colli et al., 2016) to upwards of ∼100 mgal/km (Molnar et al., 2015). Such values correspond to dynamic topography amplitudes ranging from kilometer scale to negligible for observed gravity anomalies of less than ∼100 mgal. This suggests the potential for large dynamic topography without large free-air gravity anomalies (Colli et al., 2016), but does not help to constrain the actual amplitude of dynamic topography.

Dynamic topography can be estimated directly if the isostatic component of topographic relief can be confidently estimated and removed. This is significantly simpler for seafloor than it is for continents, where crustal structures have experienced a much longer and more complex development. By contrast, the seafloor topography is dominated by half-space cooling of oceanic lithosphere, which allows us to relate isostatic subsidence of the ridge flank to the square root of seafloor age (e.g., Parsons and Sclater, 1977). Removal of this isostatic topography from seafloor bathymetry produces a map of residual topography (e.g., Flament et al., 2013; Gurnis et al., 2000; Steinberger, 2016) that should directly constrain dynamic topography (e.g., Adam et al., 2015; Hoggard et al., 2016; Steinberger et al., 2017). However, the relationship between subsidence rate and seafloor age may vary between ridge systems (e.g., Calcagno and Cazenave, 1993), and several different relationships have been proposed (e.g., Korenaga and Korenaga, 2008; Parsons and Sclater, 1977; Stein and Stein, 1992; Zhong et al., 2007). Furthermore, rates of seafloor subsidence are determined empirically, and thus incorporate any component of dynamic topography that varies systematically with seafloor age. For these reasons, fully separating isostatic and dynamic topography on the seafloor remains a challenge.

To develop a new constraint on dynamic topography, we utilize the fact that seafloor subsidence should occur at equal rates on both sides of a mid-ocean ridge (MOR), producing isostatic topography that is symmetrical about the ridge axis. Thus, if the seafloor is deflected over long wavelengths by dynamic topography, we would expect to observe an asymmetry in subsidence rates across the MOR (Fig. 1). Indeed, early studies suggested that the western flank of the Mid-Atlantic Ridge (MAR) (Calcagno and Cazenave, 1993; Marty and Cazenave, 1989) and the eastern flank of the East Pacific Rise (EPR) (Cochran, 1986) are subsiding faster than their opposing flanks. Here we examine subsidence trends across large areas of young seafloor in the Pacific and Atlantic basins, and use the resulting observations of subsidence asymmetry to develop a new constraint on the amplitude of dynamic topography that does not depend on a specific choice for the seafloor age-depth relationship.

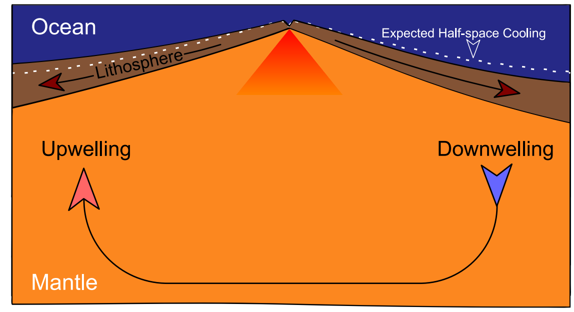

Fig. 1. Cartoon illustrating how dynamic topography creates an apparent asymmetry in half-space cooling across a mid-ocean ridge. The dashed white line represents a symmetric ridge, and the brown ridge shows the seafloor bathymetry after deflection by stresses from mantle flow. In this case, the ridge flank above a downwelling (right) is subsided and the ridge flank above an upwelling (left) is elevated, resulting in a tilted ridge cross section. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

2. Detecting ridge flank asymmetry

To constrain the amplitude of dynamic topography, we utilize the ETOPO1 model of ocean bathymetry sampled at a spacing of a tenth of a degree, or roughly 9–15 km (Sandwell and Smith, 2009). This dataset utilizes constraints from both shiptrack bathymetry and satellite gravity observations. To examine areas relatively unperturbed by local phenomena, we masked bathymetry within 100 km of large igneous provinces (LIPs) and within three times the major axis of seamounts greater than one kilometer in height (Fig. 2b). Varying the masking radii from two to five times the major radius did not significantly impact our results. Because seafloor sediments also impact bathymetry, we excluded areas with more than one kilometer of sediment and isostatically compensated sediments in the remaining areas (Fig. 2b) using the updated NGDC Ocean Sediment map (Whittaker et al., 2013) and the isostatic formulation of Sykes (1996). Abyssal hill processes generate another natural source of variability in depth measurements. We minimized the potential for aliasing by applying a 25 km Gaussian filter and bootstrapping the resulting bathymetry to average out abyssal hills and other geological anomalies along the age profile.

In order to assess the potential bathymetric asymmetry of MORs, we analyzed seafloor spanning the central MAR and EPR (white outlines, Fig. 2), as other regions of the MORs exhibit intense volcanic activity, highly asymmetric age distribution, or complex geometry. For the EPR, we examined seafloor younger than 40 Ma so that profiles would include seafloor on both sides of the ridge. In the Atlantic Basin, we used an age cutoff of 70 Ma to ensure that the dominant physical process would be half-space cooling and not seafloor flattening processes that become important for seafloor older than ∼80 Ma (Stein and Stein, 1992). We limited the North–South range of the Atlantic Basin to between 30°N and 40°S to minimize the impact of the Icelandic plume.

In order to develop a robust linear regression of bathymetry as a function of the square root of the age of the seafloor, we bootstrapped the bathymetric data by the square root of age by randomly selecting an equal number of data points for each of the 70 and 120 equally spaced square root of age bins for the EPR and MAR, respectively. This mitigates the inherent sampling bias toward younger seafloor (Korenaga and Korenaga, 2008). We performed a simple least-squares linear regression of depth versus the square root of age globally over the age range of 5 to 70 Ma and on each of the four ridge flanks studied. Applying this method globally and using 1000 points in each of the bins, we found a subsidence rate (with one standard deviation uncertainty) for ages <70 Ma of 319 ± 24 m/Myr$^{1/2}$, which agrees with the rate of 315 ± 26 m/Myr$^{1/2}$ previously reported