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Anomalous bathymetry, 3D edge driven convection, and dynamic topography at the western Atlantic passive margin

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ABSTRACT

A series of topographic/bathymetric anomalies trend along the western passive plate margin of the North Atlantic and are characterized roughly by uplift offshore on the ocean plate and subsidence at the continental margin. The features—determined from two independent data sets—are not constant along the strike of the plate boundary, however. The anomalous topography/bathymetry is considered to be a surface dynamic response to edge driven convection in the mantle occurring at the continental margin. Three-dimensional numerical mantle flow experiments are conducted to investigate the margin-parallel and -perpendicular development of edge driven convection and dynamic topography. The flow induces a near-margin topography low and offshore bathymetry high of up to ~1.5 km. If the thermal structure of the convection is perturbed along strike to the plate boundary, the edge driven convection cells develop instabilities with a similar ~500 km wavelength. This causes localized peaks and saddles in the topography/bathymetry that is consistent with the observed variability of residual topography along the western side of the North Atlantic. The plate margin experiences modest thermal erosion causing dynamic topography to migrate continent-ward and slightly increasing its wavelength. Generally, though, the flow and associated topography developed into a quasi-static form relative to the passive margin over timescales of at least tens of millions of years.

1. Introduction

Oceanic lithosphere exhibits a consistent and well-understood increase in bathymetry from mid-ocean ridges to passive continental margins (Turcotte and Schubert, 2002). However, the plates also contain more enigmatic, shorter wavelength bathymetric features superimposed on the plate cooling and subsidence phenomenon. Some of these features may be caused by the relative motion of the ocean plate over hot spots, resulting in a track of elevated seamounts parallel to the direction of the plate motion (e.g., Wilson, 1963). The topographic anomalies can also be caused by various processes such as seafloor volcanism, post-rift epeirogeny (Conrad et al., 2004), and flexural loading, but this contribution focuses on the possibility that some of the bathymetric features (or at least some component of their anomalous bathymetry) are a manifestation of dynamic topography. Dynamic topography is defined as vertical motions of the surface caused by imposed normal stresses at the base of the lithosphere from underlying mantle flow (McKenzie, 1977; Cazenave et al., 1989; Kido and Seno, 1994).

At a passive continent–ocean margin, a sharp lateral variation in thermal structure of the lithosphere may induce the formation of a convective mantle fluid flow (Elder, 1976). This style of convection was studied by King and Anderson (1995) as a process to account for the formation of flood basalts near the margins of cratonic lithosphere. The term "edge driven convection" (EDC) was put forward to denote such a regime of mantle convection induced by the sharp lateral thermal gradient as a continent–ocean boundary (King and Anderson, 1998). The thermal discontinuity can initiate a small-scale mantle convection cell with downwelling at the continental margin and corresponding upwelling further offshore. Ritsema et al. (1999) and King and Ritsema (2000) infer that velocity anomalies in the upper mantle in the tomographic model S20RTS delineate the thermal anomalies of edge driven convective flow along portions of eastern North America, western Africa and eastern South America. They put forward EDC as an explanation for intraplate African and South American hotspot volcanism (Ritsema et al., 1999; King and Ritsema, 2000; King, 2007).

A prominent group of bathymetric and thermal anomalies exists in the western Atlantic adjacent to the passive continent–ocean margin. Vogt (1991) put forward several reasons why several of these specific topographic swell patterns (including the Bermuda Rise) could not be reconciled with simple hot spot theory. Firstly, the lack of volcanism on or in the vicinity of Bermuda during the past 33 Myr precludes an active mantle plume source for support-

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ing the topography. Secondly, the orientation of the Bermuda Rise is almost orthogonal to the predicted fixed hot spot track associated with North American plate motion. Vogt (1991) suggested that these anomalous topographic features may be produced by a thermal instability traveling with the North American plate rather than a deep mantle plume. That is, a process akin to the subsequently proposed edge driven convection (King and Anderson, 1995).

Edge driven convection (EDC) within the upper mantle produces a topographic perturbation that may be consistent with bathymetric perturbations at a passive plate boundary (King and Anderson, 1998). Two-dimensional modeling shows that such EDC induces subsidence at the continental margin and an offshore peak/plateau of high topography on the ocean plate (Shahnas and Pysklywec, 2004). Conrad et al. (2004) proposed that the downgoing portion of a potential edge driven mantle convection cell may cause an anomalously deep region off the coast of Nova Scotia. Unlike a hot spot, the edge driven convection cell and associated topography migrate with moving surface plates. As a result, EDC-related topography on the seafloor would not show a track of bathymetry, but rather would develop in a quasi-stable geographic location. The amplitude and wavelength of the dynamic topography could vary in time, especially in the presence of a simulated surface plate motion (Shahnas and Pysklywec, 2004). However, the two-dimensional models did not give any insight into how the flow/topographic features varied in the direction parallel to the strike of the passive plate boundary.

The purpose of this work is to consider the variation of topography along the eastern seaboard of North America and the three-dimensional (3D) nature of EDC. A 3D examination may be important in our understanding of this small-scale convective phenomenon. The investigation extends the previous 2D studies by determining the anomalous bathymetry/topography at a number of profiles along the passive margin of the continent. Further, 3D geodynamic computational experiments are executed to model the edge driven mantle flow and associated surface topographic features, or lack thereof, in the 3D geodynamic models. The long-wavelength topographic/bathymetric anomalies of the region are considered to be dynamic topography associated with EDC. Taken into primary consideration are the stability and longevity of the continental margin and the imposed viscosity structure of the ocean–continent lithosphere (Shapiro et al., 1999).

In this study, the focus is on the topographic expression of mantle convection and the observed topographic anomalies. It is recognized that there exists a thermal expression and thermal anomalies of the edge driven convection as well. Certainly, magmatic features of Bermuda and the Bermuda Rise are prominent and are transient in nature (Vogt, 1991; Harris and McNutt, 2007). Furthermore, thermal alteration of the ocean plate due to these magmatic effects may contribute to topography anomalies but this is not considered here.

2. Anomalous topography in the western North Atlantic

Various data have been compiled to demonstrate the anomalous bathymetry/topography across the western part of the North Atlantic and Eastern seaboard of North America. The first set is shown as a series of profiles approximately perpendicular to the continental margin (Fig. 1). These bathymetric anomalies were derived by correcting the observed seafloor bathymetry for cooling and subsidence of the ocean plate away from the mid-Atlantic ridge and isostatic sediment loading. Two sources of data were used: (1) Sclater and Wixon (1986) and (2) Louden et al. (2004). The former was used for the two profiles (F–F′, G–G′) north east of the New England Seamount chain and the latter for the more southerly profiles. A similar approach was used in both studies, but differing parameters in the cooling/subsidence calculations and availability of sediment thickness information mean the two sets of results are not entirely consistent. Unfortunately, there is little overlap between the Sclater and Wixon (1986) and Louden et al. (2004) data, which prevents us from comparing directly the two sets of results across similar profiles.

The onshore (i.e., continental) portions of the topography anomalies are derived from a correction to topography that removes the isostatic contribution of crustal thickening. For the correction, the CRUST2.0 database (Bassin et al., 2000) was used, which gives crustal thickness and density in $2^\circ \times 2^\circ$ cells. The continental topographic anomalies were extrapolated to the bathymetric anomalies across the continental shelf margin for each profile; in general, there was good continuity between the anomalies across the margin (Fig. 1).

Together, the onshore/offshore topography anomalies quantify the topographic residuals—possibly reflecting a remaining dynamic topographic signal—by removing the primary isostatic components for oceanic and continental lithosphere. One of the primary features of the anomaly profiles is a bathymetric high out on the ocean plate (Fig. 1). For the southerly profiles (A–A′, B–B′, C–C′, D–D′) this corresponds to the Bermuda Rise, which rises ∼800 m above the nominal seafloor surface. For the profile F–F′ the elevated bathymetry is related to the Corner Rise and for G–G′ the high occurs near to the mid-Atlantic ridge (note that the ridge topography should be corrected for in the Louden et al., 2004 calculations). These bathymetric highs trend approximately parallel to the continent–ocean plate boundary (i.e., the continental shelf), varying from 700 to 1500 km offshore. Profile E–E′ is a bit exceptional in that it shows a broad rise out onto the ocean plate perpendicular to the continent–ocean boundary as it traces parallel through the New England Seamount chain. These bathymetric highs trend approximately parallel to the continent–ocean plate boundary (i.e., the continental shelf), varying from 700 to 1500 km offshore.

Conjugate to the elevated bathymetry there is subsidence at the continental margin (Fig. 1). This reaches ∼400 m amplitude for the southerly profiles and extends beneath the continental plate. Anomalous subsidence also occurs off the margin of Nova Scotia (F–F′); this deepening of the Scotian Basin was also previously observed by Conrad et al. (2004) and Louden et al. (2004). Clearly, though, the deepening also occurs all along the Eastern seaboard of North America.

Although there seems to be a margin-parallel trend of the conjugate offshore high/onshore low of topography, the topographic (and magmatic) features do not occur consistently along the extent of the margin. This is apparent even in the raw topography/bathymetry map where the series of seafloor features trend commonly, but unevenly, along strike of the continental margin.

The profiles can be compared with a full map of residual topography derived from the CRUST2.0 database (Fig. 2). The residual bathymetry data here are spatially coarser than the calculated residuals from Sclater and Wixon (1986) and Louden et al. (2004) and do not correct for cooling and subsidence of the ocean lithosphere. However, the data demonstrates large-scale trends—in directions both away from the trench and parallel to the passive margin. As in the other data sets, the CRUST2.0 map shows a series of residual bathymetry lows offshore along eastern coast of North America. These deepenings are not continuous along the margin, but develop as localized subsidence basins; once established, sediment loading would further deepen such basins. An anomalous high bathymetry residual occurs approximately 800 km offshore—corresponding with the Bermuda Rise. Again, this feature does not stretch continuously along the strike of the continental margin, although it does extend broadly in this direction—certainly over a longer wavelength than the deepenings at the margin.