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Satellite magnetic anomalies related to seafloor spreading in the South Atlantic Ocean

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Abstract. Oceanic magnetic anomalies have been observed from satellite. The strongest anomalies are the long-wavelength components of the sea-floor spreading signature. Unfortunately, because of technical issues involving the treatment of satellite magnetic data, these signals are obscured in the South Atlantic Ocean because they trend north-south. However, a map does exist in which such features are observed, essentially because of a better data processing technique. Further, this map agrees with a physically motivated model based on non-satellite magnetic input. Hence, with properly treated data, the magnetic anomaly maps should be useful for saying something about the geology, rather than vice-versa. This situation will be considerably improved by ongoing advances in methods and new data sets. The amplitude of the observations, a factor of two larger than previous estimates, confirms that the extrusive basaltic layer alone is inadequate to produce the signal and that deeper oceanic sources are required.

Introduction

Mapping the lithospheric magnetic anomaly field from satellite enhances our knowledge of the oceanic lithosphere, especially in frontier areas like the South Atlantic. Focused studies such as these, where a detailed model is compared to observations, allow for evaluation of the satellite signal in high noise areas. The South and Equatorial Atlantic region is an area where non-lithospheric magnetic signals (the 'noise' of this paper) are strong and variable [*Langel et al.*, 1993].

Unlike the Central Atlantic, Pacific and southwestern Indian Oceans, which all display strong satellite magnetic anomalies associated with the Cretaceous Quiet Zones (KQZs; see review in *Langel and Hinze* [1998]), no significant signature of the KQZs or other mid-ocean ridge parallel features has been recognized so far on a satellite magnetic anomaly map of the South Atlantic. However, indirect evidence for the KQZ on the African side has been suggested [*Fullerton et al.*, 1989]. Conversely, global models of the satellite magnetic anomalies arising from the remanent magnetization of the KQZs [*Cohen and Achache*, 1994] or of the whole oceanic lithosphere [*Dyment and Arkani-Hamed*, 1998] predict strong anomalies associated with the KQZs and the Mid-Atlantic Ridge. As has been suggested [*Purucker et al.*, 1998; *Dyment and Arkani-Hamed*, 1998], this discrepancy is likely related to the characteristics of the along-track filters applied in order to remove external fields, which will tend to selectively remove north-south trending components of the lithospheric anomalies in satellite magnetic anomaly maps like those of *Arkani-Hamed et al.* [1994] and *Ravat et al.* [1995].

One magnetic satellite anomaly map does indeed retain north-south features which resemble those predicted by the global models. This 'map', by *Cain et al.* [1990], has previously been available only as a set of spherical harmonic coefficients, which may have hindered proper evaluation in the space domain. A comparison of the satellite magnetic anomaly map of *Cain et al.* [1990] with the model of *Dyment and Arkani-Hamed* [1998] over the South Atlantic Ocean allows us to 1) investigate the magnetic structure of the South Atlantic Ocean, 2) evaluate the impact of the along-track filtering technique on previous results concerning the magnetic structure of the oceanic lithosphere, and 3) evaluate the quality of the *Cain et al.* [1990] map. We use the term 'map' in this paper to refer to satellite observations of the magnetic field, in contrast to the term 'model' which we restrict to physically motivated models based on non-satellite magnetic input.

The Observations

Cain et al. [1990] coestimate the core and lithospheric fields up to degree and order 49. The vector and scalar magnetic fields from the Magsat data set were used in an estimation procedure based on least-squares and Gauss- Legendre quadrature. This estimation was done subsequent to a first-order correction for magnetospheric and ionospheric fields. The magnetospheric ring current field was assumed proportional to the D_{st} index and the geomagnetic latitude. Ionospheric fields were modeled with a harmonic function of the dip latitude. The data was fit separately for dawn and dusk local times and the ionospheric field values shown as solid lines in Figure 3 of *Cain et al.* [1989a] were removed from each dawn and dusk half-orbit.

The resulting set of spherical harmonic coefficients, termed $M102389$, extend to degree and order 49. This set of coefficients, one of several derived by Cain and his colleagues, was used by *Langel and Hinze* [1998] in their comparative study of magnetic anomaly maps.

What spherical harmonic degrees (n) should be used to study the lithospheric field? In order to answer this question we need to determine both the transition from core to

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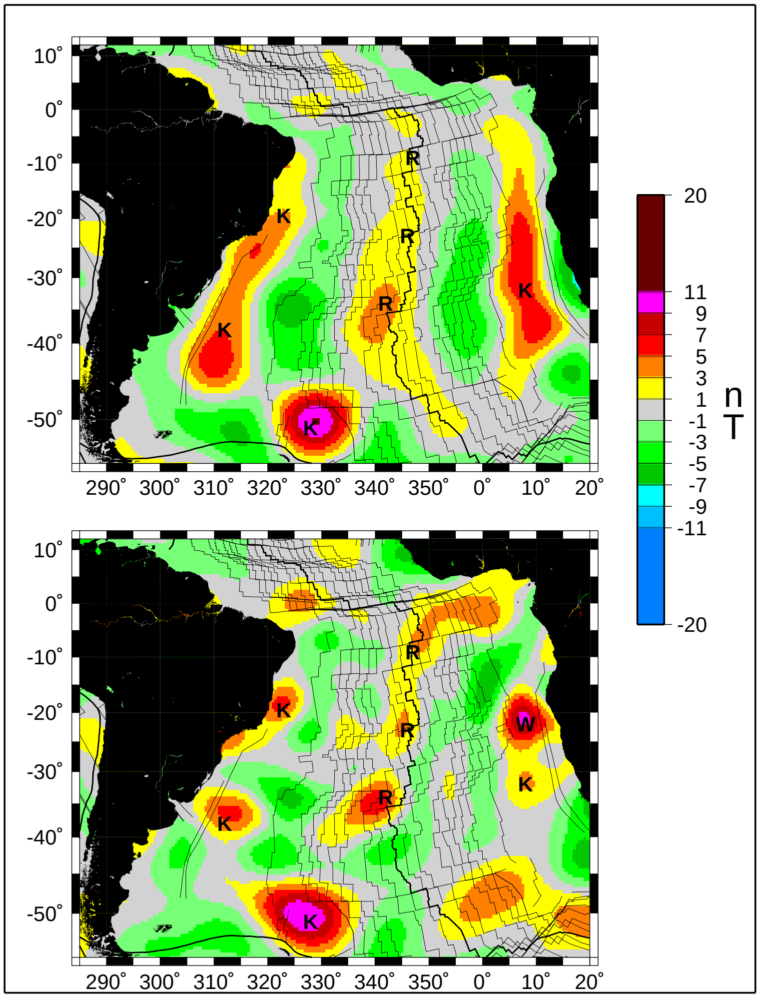

Plate 1. A comparison of the model (top) with the observations (bottom). Both model and observations are restricted to the spectral range 15-40 and are displayed at an altitude of 400 km. Sea-floor spreading isochrons are shown as solid black lines in the Atlantic and the mid-Atlantic ridge is shown as a thick black line. K identifies anomalies due to the Cretaceous quiet zone. R identifies anomalies due to the spreading ridge. W identifies the Walvis ridge anomaly.

lithospheric field and the transition from lithospheric field to noise. Complicating this selection is the fact that both transitions take place over a range of spherical harmonic degrees and that the expected form of the crustal field spectrum is unknown [*Jackson*, 1990].

One criterion for separating core and lithospheric field spectra is to find the point where the energy density of the two components become equal at the Earth's surface. *Cain et al.* [1989b] found this to be $n = 14.2$. This is consistent with other worker's estimate of the separation [*Langel and Hinze*, 1998] and with a least-squares fit of the two best-fitting straight lines to the Mauersberger- Lowes spectrum [*Lowes*, 1974] of $M102389$.

The transition from lithospheric field to noise can be examined by considering the relationships between the vector components that must be satisfied for an internal potential field [*Parker and O'Brien*, 1997] generated by a statistically stationary source. *Lowe et al.* [1999] have recently found that for Magsat vector field measurements, this transition occurs between $n = 37$ and $n = 40$. A change in the slope of the spectrum of $M102389$, identified by least- squares fitting, occurs at degree 40. Therefore, we have selected degrees 15-40 to study the lithospheric field and to compare with the model to be described next. The model is also limited to degrees 15-40.

The Model

Dyment and Arkani-Hamed [1998] have modeled the remanent magnetization of the oceanic lithosphere and its contribution to satellite magnetic anomalies. This model is a physically motivated one based on non-satellite magnetic input and subsequently calibrated so that modeled and observed KQZ anomalies in the North Atlantic have similar amplitudes. The magnetization vector direction and the variation of its intensity with paleolatitude have been determined using ocean floor ages, relative motion parameters for each plate, and the apparent paleomagnetic polar wander path for Africa. The variation of magnetization intensity with age has been obtained using the model of *Arkani-Hamed* [1989] for the vertical distribution of thermoviscous remanent magnetization in the oceanic lithosphere, which was vertically averaged to compute the resulting magnetic anomaly at satellite altitude. That model simulates the acquisition of magnetization with time in each lithospheric column, given a thermal evolution model, the geomagnetic polarity time scale, and the magnetic properties of the various materials in the column. *Dyment and Arkani-Hamed* [1998] have tested different hypotheses and showed that the distribution of magnetization which best fit the shape and amplitude of the oceanic anomalies in the *Arkani-Hamed et al.* [1994] map assumes a 12 km thick magnetic layer, with maximum magnetization of 4, 0, 1, and 0.6 A/m for the extrusive basalts (0-0.5 km deep), intrusive basalts (0.5-2 km), gabbros (2-6 km), and peridotites (below 6 km), respectively. The intensity of magnetization was adjusted to fit the KQZ anomalies in the Central Atlantic Ocean as observed on the map of *Arkani-Hamed et al.* [1994], and provided a good fit in other areas such as the KQZs of the Southwestern Indian Ocean and the anomalies parallel to the Southeast Indian and Pacific-Antarctic Ridges. In part because their technique retains power that has been removed by along-track filtering in other maps, *Cain et al.* [1990] obtained anomalies which are about twice as strong as in the map of *Arkani-Hamed et al.* [1994]. A further explanation for the low amplitude of the *Arkani-Hamed et al.* [1994] map is the stringent criteria applied in correlating the dawn and dusk Magsat maps. Relaxation of these stringent criteria, at the expense of stronger external field contributions, results in anomaly magnitudes which may be 50% higher [*Arkani-Hamed et al.*, 1994]. The model of *Dyment and Arkani-Hamed* [1998] was therefore recalibrated using the new map, resulting in a doubling of the magnetization used in the model. Comparison of the newly calibrated model with the map of *Cain et al.* [1990] in areas outside of the South Atlantic reveals a good agreement between anomaly amplitudes and form in the Central Atlantic and Southwestern Indian oceans. There is also a good correspondence in amplitudes near the Southeast Indian and Pacific- Antarctic ridges. Plate 1 (top) shows the map of the model in the degree 15-40 range. A global version of Plate 1 and associated materials are available in digital form from the authors' web site (http://denali.gsfc.nasa.gov/research/purucker/south_atlantic_mag.html).

Interpretation and Discussion

The longest N-S anomalies remaining in the observations (Plate 1, bottom) are $\approx 30-40^\circ$ in latitude length. In contrast, the ionospheric filter applied in previous studies [*Ravat et al.*, 1995; *Arkani-Hamed et al.*, 1994] removes north-south features longer than $\approx 20^\circ$ in latitude length. So only short segments of the north-south magnetic anomalies related to seafloor spreading will have survived in these previous maps.

A comparison between model and observations over the South Atlantic (Plate 1) allows the recognition of 1) the Cretaceous quiet zones (K, Plate 1), 2) the period of more rapid field change in the Tertiary, and 3) the enhanced signal over the spreading ridge (R, Plate 1). This is the first time these features have been identified from satellite in this area. The observations also show other, previously recognized features of the satellite field in the South Atlantic, including that over the Walvis ridge (W, Plate 1), probably supplemented by a Cretaceous quiet zone signal [*Fullerton et al.*, 1989] and the Cretaceous quiet zone signal over the South Sandwich islands.

The amplitude of some anomalies suggests that the basaltic layer is inadequate to produce the signal observed at satellite altitude and that deeper oceanic sources are required. If the extrusive basalt layer was to be considered as the only source of the satellite anomalies (see Model 1 of *Dyment and Arkani-Hamed* [1998]), a maximum magnetization of 32 A/m (for a 0.5 km thick layer) would be required, which is unrealistic compared to the intensity of remanent magnetization measured in rocks older than 1 Ma (see *Dyment and Arkani-Hamed* [1995] for a review).

We have looked for other features expected to give lithospheric signals in the *Cain et al.* [1990] map and have not seen them. These include the Rio Grande Rise as well as the Tristan da Cunha, Saint Helena, and Ascension island hotspots. We attribute this, in part, to noise which still contaminates the M102389 map. Conversely, some of 'signal' not explained by the *Dyment and Arkani-Hamed* [1998] model is difficult to interpret in terms of lithospheric sources. For this reason, the upcoming CHAMP satellite mission [*Reigber et al.*, 1999] to map the Earth's magnetic field at altitudes below 460 km will be especially important because one of its goals is a detailed mapping of the oceanic anomaly field. A further extension of the coestimation methodology of *Cain et al.* [1990] to include external fields [*Purucker et al.*, 1997] will also allow a better estimate of covarying external and internal fields, and therefore provide a better estimate of the north-south trending lithospheric field. These techniques, which are still in development [*Sabaka et al.*, 2000], will also provide a more physically-based description of the external fields and account for induced fields produced by conductivity variations between ocean water and solid rock.

The map of *Cain et al.* [1990] probably reflects a better estimate of north-south anomalies that are $20-40^\circ$ in length than the map of *Arkani-Hamed et al.* [1994]. In contrast, the *Arkani-Hamed et al.* [1994] map probably contains fewer external field signals than the map of *Cain et al.* [1990].

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