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Key Points:
- Remanent magnetization of the extrusive oceanic basalt is partly or completely removed due to abundant post-accretion sedimentation
- This effect should be considered when interpreting marine magnetic anomalies across passive margins and other heavily sedimented areas

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The Influence of Post-accretion Sedimentation on Marine Magnetic Anomalies

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Abstract Marine magnetic anomalies are a critical observation used to investigate seafloor spreading and the transition between oceanic and continental crust at passive margins. However, pronounced post-accretion sedimentation disturbs the thermal state of the crust and therefore alters its remanent magnetization. To study the link between sedimentation and magnetization of the oceanic crust, we built a series of thermomagnetic forward models coupled with different sedimentation histories. We test our approach against observations from the early Cretaceous southern South Atlantic Ocean. Our simulations suggest that, depending on the thickness of post-accretion sediments, the remanent magnetization of the extrusive basalts is partly or completely removed. Therefore, the typical long-wavelength sea surface marine magnetic anomalies observed above oceanic crust covered by a thick sedimentary pile is almost entirely generated by the magnetization of the deeper crustal layers.

Plain Language Summary Marine magnetic anomalies are a critical observation used to investigate seafloor spreading and the transition between oceanic and continental crust at passive margins. Here we show that the accumulation of sediments over the oceanic crust has a thermal effect, which can lead, under certain conditions, to the complete removal of magnetization in the upper oceanic crust. This, in turn, may have important consequences for how we understand passive margins and the accuracy of plate kinematic models.

1. Introduction

The acquisition of thermoremanent magnetization by the igneous oceanic crust as it drifts from the mid-ocean ridges and cools has proven remarkably useful for the investigation of various geodynamic phenomena. The magnetization is predominantly carried by titanomagnetite (Gee & Kent, 2007; Lowrie et al., 1973; Shau et al., 2000) having varying titanium content (Rubin & Sinton, 2007) and hence the blocking temperature by which the magnetization is locked spans over a large range of temperatures (i.e., ~100 up to ~580 °C). Although the magnetic carriers are sensitive to the post-accretion crustal thermal history, the existence of similar lineated marine magnetic anomalies found on conjugate sides of the different oceanic basins (e.g., Cande et al., 1989; Seton et al., 2014) suggests that, to a first degree, crustal remanent magnetization remains virtually intact. For that reason, post-accretion deposition of sedimentary sequences that leads to elevated temperatures within the oceanic crust was thus far mostly ignored in the context of sea surface marine magnetic anomalies. In certain areas, especially where thick sedimentary sequences exist (e.g., at and near passive margins), the thermal effects of the sediments on crustal magnetization could potentially be significant and might help to resolve some of the ambiguities related to the interpretation of continent-ocean boundaries from marine magnetic anomalies (e.g., Eagles et al., 2015).

An ideal test bed for illustrating the possible effect of post-accretion sedimentation on marine magnetic anomalies would be an area that preserves both conjugate flanks of a mid-ocean ridge, which are covered by a markedly different thickness of sedimentary sequences. Any difference in the shape of the conjugate magnetic anomalies, beyond the expected variance due to the different depth to the basement and other local magnetic and spreading conditions (i.e., direction of the ambient geomagnetic field and remanent magnetization, azimuth of lineation, and seafloor spreading rates), which are relatively well known, could reflect the impact of the sedimentary sequences on magnetization. Such an area exists in the early Cretaceous southern South Atlantic, between anomalies M0 and M6 (121 and 127 Ma, respectively; Malinverno et al., 2012) where the conjugate South American and African flanks are covered by 6 to 9 and 2 to 4 km of sediments, respectively (Figure 1; Hoggard et al., 2017). Interestingly, the observed magnetic profiles crossing these two flanks

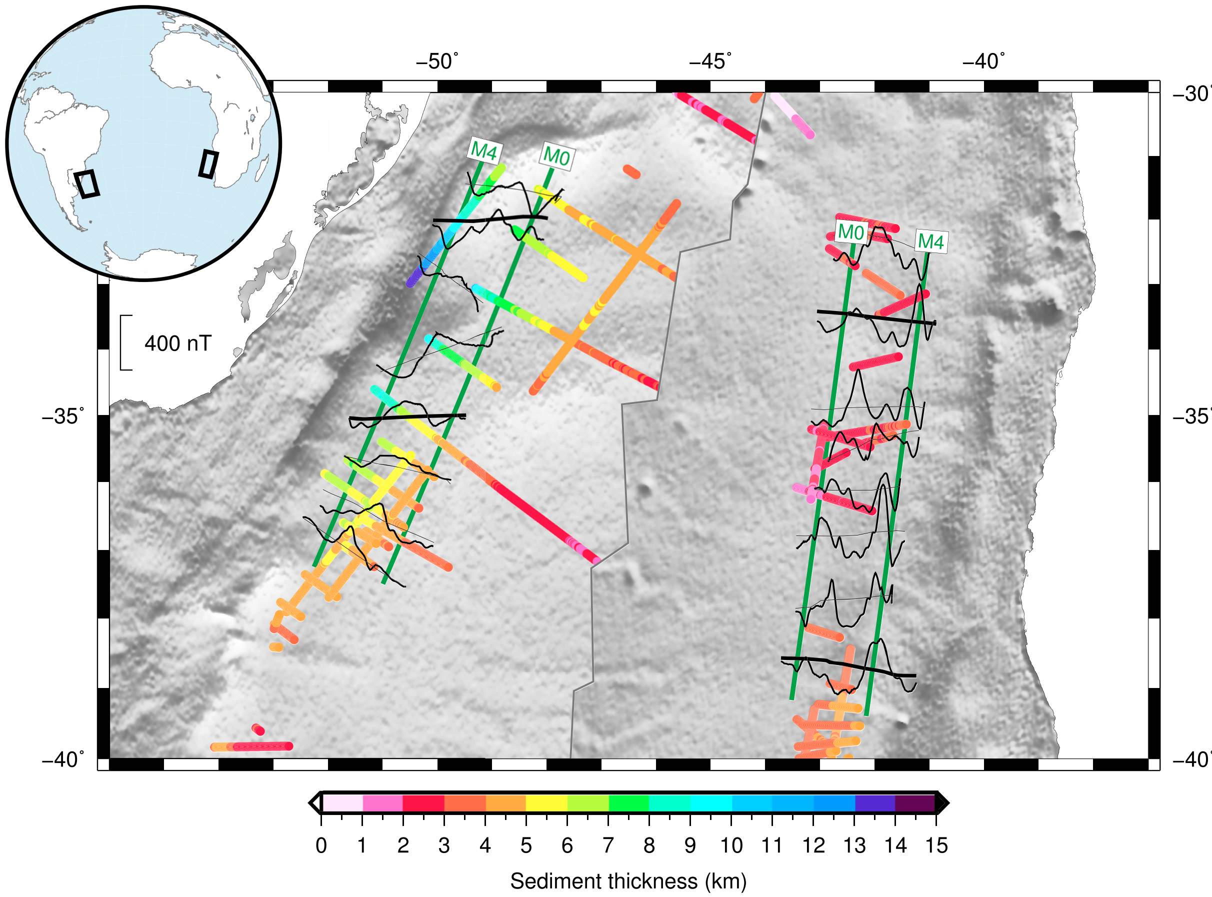

Figure 1. Mesozoic marine magnetic anomalies collected across the flanks of the southern South Atlantic basin. Background gray map is the satellite-derived gravity grid (Sandwell et al., 2014) reconstructed for the 108-Ma time (South America is fixed, rotation angle is taken from Granot & Dyment, 2015). Colored stripes show the sedimentary thicknesses calculated along seismic profiles (Hoggard et al., 2017). Magnetic anomaly profiles (National Center for Environmental Information) are plotted with positive projected northward. Magnetic profiles shown with thick lines are projected in Figure 3. Green lines mark the locations of the M0 and M4 isochrons.

have markedly different shapes that cannot be perfectly matched by the standard rectangular forward magnetic anomaly models (Figures 2 and 3). The short-wavelength (15 to ~30 km) anomalies are mostly missing from the South American anomalies (5% to 15% of the expected power is observed; Figure 2), whereas the short-wavelength spectra of the African anomalies is only partly reduced (20% to 30% of the expected power is observed; Figure 2). To better understand the possible influence of the sediments on the crustal magnetization, we first constructed a series of forward magnetic models based on simulations of magnetization acquisition through time given the different thermal and sediment deposition history of the two flanks. We then compare our results with the observations from the southern South Atlantic basin and show that sedimentation could have an important demagnetization effect on the upper oceanic crust.

2. Thermomagnetic Modeling

A realistic approach for modeling marine magnetic anomalies that takes into account both the thermal evolution of the oceanic lithosphere and the magnetic properties of its constituents has been previously applied to the study of the shape (skewness) of the anomalies (Arkani-Hamed, 1991; Dyment et al., 1997; Dyment & Arkani-Hamed, 1995). In this approach, first the thermal evolution of the oceanic lithosphere is calculated assuming a half-space model where the lithosphere is conductively cooling from the top. To account for the acquisition of both the thermoremanent magnetization and the secondary viscous remanent magnetization, the theoretical blocking curves of single domain titanomagnetite carriers (Pullaiah et al., 1975) are adopted. The models assign, for each time step, a positive or negative magnetization component based on the

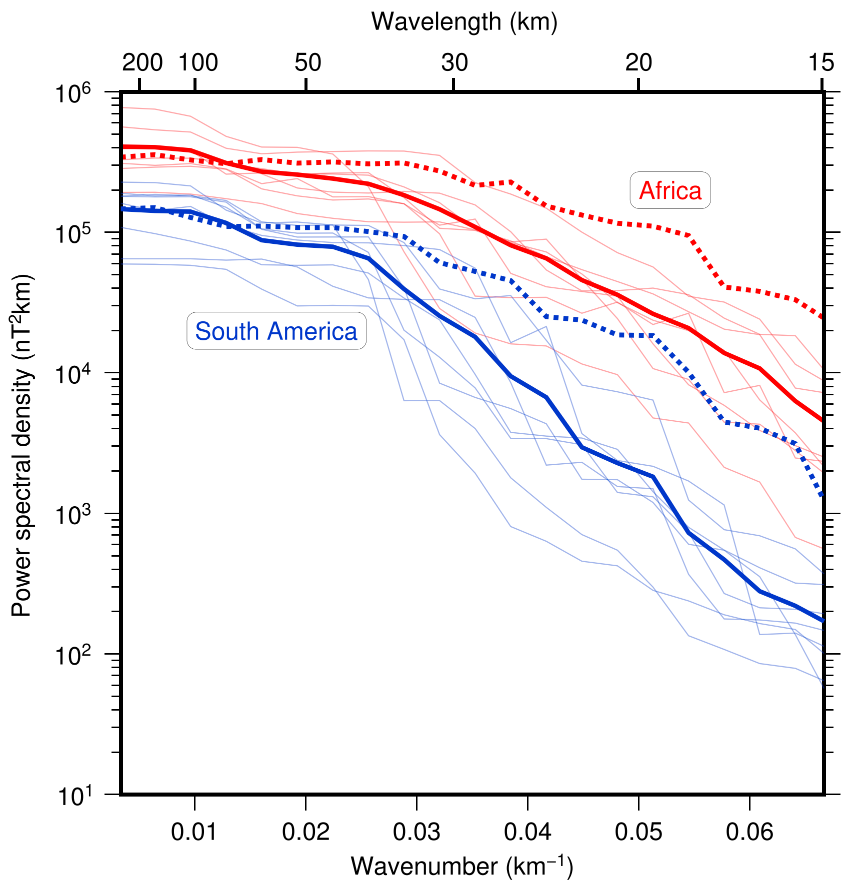

Figure 2. Multitaper spectral analysis (Prieto et al., 2009) of the sea surface magnetic anomalies. Thin red and blue lines show the spectra of the 16 African and South American magnetic profiles shown in Figure 1, respectively. Thick lines delineate their averages. Dashed lines show the spectra of the standard forward magnetic anomalies (black lines in Figure 3). A time-bandwidth product of 4 and 8 tapers were used. Due to the band pass Earth filter (Schouten & McCamy, 1972), only wavelengths longer than 15 km can potentially be preserved.

geomagnetic polarity state as being defined for the Cenozoic (Cande & Kent, 1995) and Mesozoic (Malinverno et al., 2012). We modified this thermoviscous remanent magnetization modeling approach to include the thermal effect of the post-accretion sedimentary sequence deposited on top the oceanic crust. We assumed that no internal heat is being generated within the sediments and assigned 0 °C as the thermal boundary condition to the top of the sedimentary layer (i.e., seafloor). For simplicity, we assumed that the temperatures within the sediments and in the top of the oceanic crust reach steady-state conditions immediately after deposition. Since in reality the temperatures are slowly increasing (over ~10^7 million of years) before they reach the steady-state conditions, our results provide an upper limit, conservative perspective for the influence of sedimentation on magnetization. The sediments are assumed to have negligible natural remanent magnetization (NRM) and thus were not used in the calculation of the anomalies. We assigned saturation NRM values following the compilation of Gee and Kent (2007) whereby the extrusive basalt, sheeted dike, and gabbro layers have NRM values of 6, 2, and 1.5 A/m, respectively (Figure 4). We constructed a series of forward models for which we computed the magnetization and resultant anomalies for the last 140 million years at a time interval of 0.1 Myr, the equivalent of 2.5 km at the half seafloor spreading rate of 25 km/Myr that is appropriate for the southern South Atlantic (Granot & Dyment, 2015). As illustrated by Figure 2, sedimentation may lead to the attenuation of the high frequency content, and we therefore investigate its influence on crustal magnetization, the source of such anomalies, and computed the magnetization down to a 6-km depth below the top of the basalt. The basalt, sheeted dike and gabbro layers were assigned 0.5, 1, and 4.5 km thicknesses, respectively.

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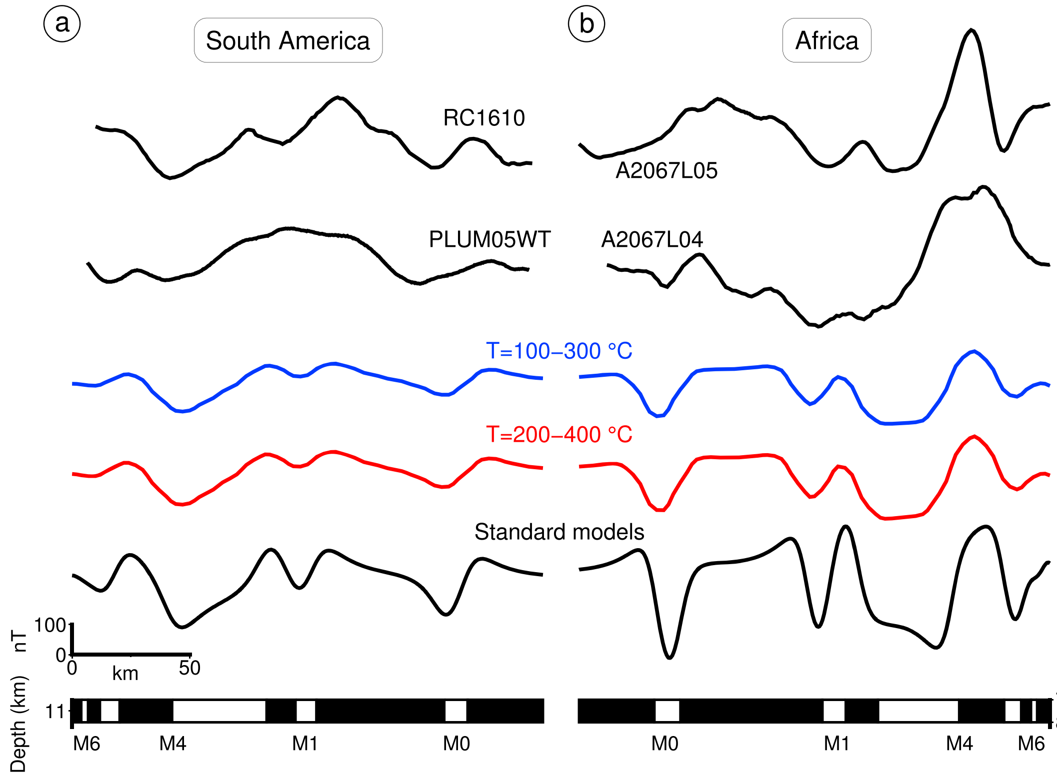

Figure 3. Observed and forward-modeled magnetic anomalies shown for the South American (a) and African (b) southern South Atlantic flanks. Bottom profiles show the results from the standard, simple rectangular magnetized prisms forward magnetic modeling. We used 1-km-thick magnetic source layer with magnetization of 8 A/m. Ambient and remanent magnetization directions were based on Thébault et al. (2015) and Torsvik et al. (2012), respectively. The colored profiles are the total magnetic anomalies computed with the coupled thermomagnetic forward modeling approach that takes the effect of post-accretion sedimentation into account. Red and blue magnetic profiles show the expected anomalies when using basalt-blocking temperatures of 200–400 and 100–300 °C, respectively. These profiles were taken from the models shown in Figure 4 (black profiles), where the results were skewed and scaled to take into account the actual ambient and remanent magnetization directions and azimuth of seafloor spreading of the two flanks of the southern South Atlantic. Note that the location of the anomalies shown along these four profiles is displaced outward due to the demagnetization of the upper crust (Figure 4). Therefore, their locations (not their shape), for the purpose of comparison, were shifted backward. Four representative magnetic anomaly profiles (black lines) are shown at the top (for locations see Figure 1).

Accurate knowledge on the characteristics of the sedimentary sequences deposited on top of the early Cretaceous flanks of the southern South Atlantic is required in order to reconstruct its crustal thermal setting hence its magnetization. The global sedimentary thickness grids have significant uncertainties in regions of thick sedimentary sequences, such as those adjacent to continental margins (e.g., Laske & Masters, 1997), therefore we adopted the sedimentary thickness values that were constructed along multichannel seismic reflection profiles and wide-angle experiments (Figure 1; Hoggard et al., 2017). In the regions of abundant sedimentation, such as the studied area, the reported uncertainties on these estimations can reach 400 m. The deposition histories of the South American (Morales et al., 2017) and African (Dressel et al., 2015) flanks, based on seismic and well data, were inserted in the models (Figures 4a and 4b).

The blocking temperature ranges used while modeling the magnetization of the different layers have critical effect on the resultant magnetization. Unlike the deeper gabbros and sheeted dikes where the magnetization is generally carried by magnetite with low titanium content, for which a characteristic blocking temperature range of 400 to 580 °C is the most appropriate, the magnetic carrier of the basaltic lavas is titanomagnetite with variable titanium content (Gee & Kent, 2007). Hence, irregular ranges of blocking temperatures have been observed for different drilled lavas. We therefore constructed a series of models that aim to cover the entire span of the blocking temperatures commonly observed in the upper basaltic samples (Figure 4).

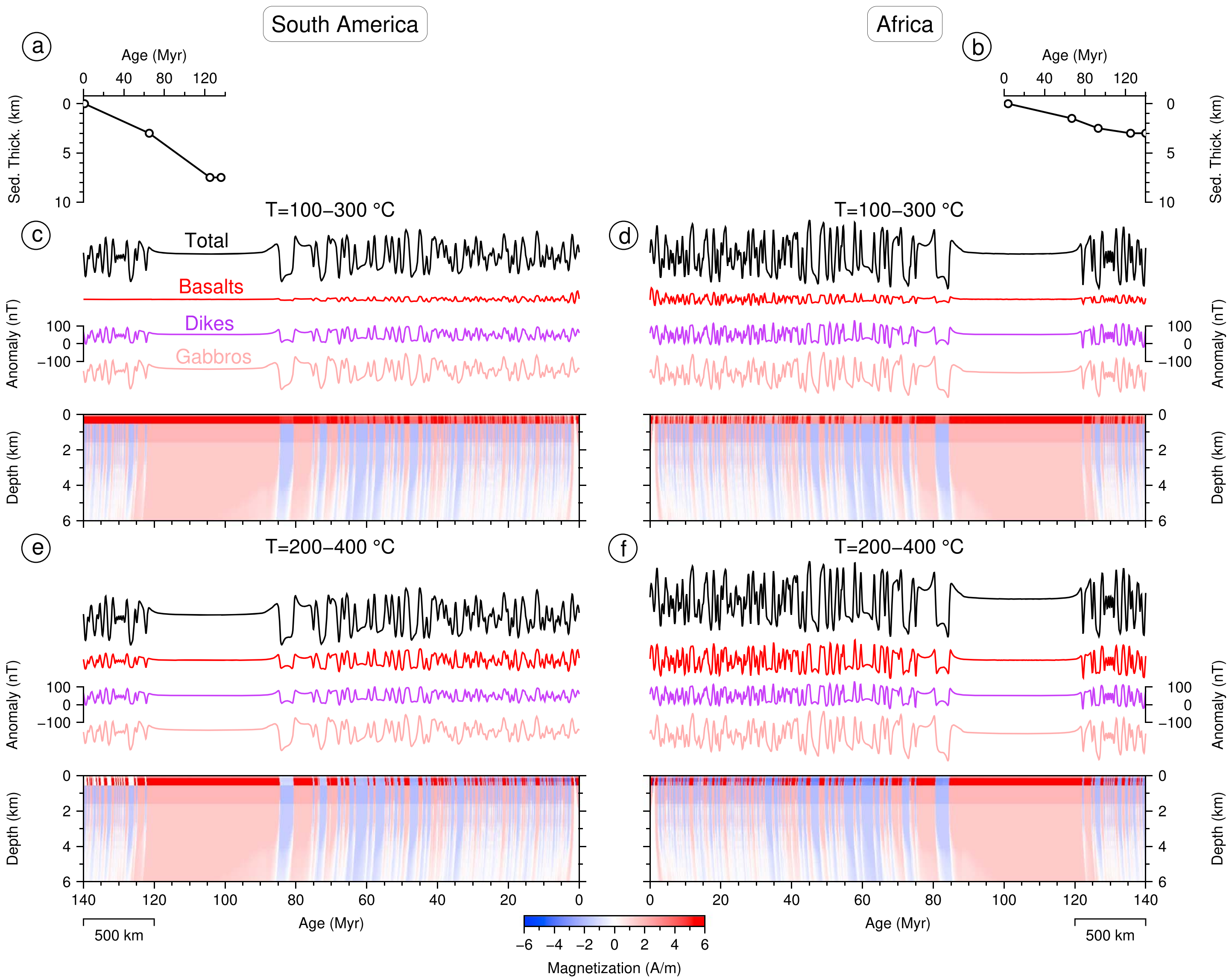

Figure 4. Results from the thermomagnetic forward modeling. (a, b) Sedimentation rate curves of the investigated Cretaceous-aged South American (a; Morales et al., 2017) and African (b; Dressel et al., 2015) southern South Atlantic flanks that were incorporated into the models. (c–f) Magnetization grids and the resultant magnetic anomalies. The anomalies are computed separately for the gabbro, sheeted dike and basalt layers and are shown in light red, purple, and red, respectively. The sum of these three contributions is shown in black. In all models, the blocking temperatures for the sheeted dikes and gabbros range between 400 and 580 °C. The blocking temperatures of the basalts were simulated with ranges of 100 to 300 °C (c, d) and 200 to 400 °C (e, f). These models were constructed using constant 7- and 10-km depths for the African and South American top of the basalt layer, respectively.

The results from the thermomagnetic modeling provide important new insights to the origin of magnetic anomalies on crust with abundant sedimentation. The lower crustal gabbros and the sheeted dikes display similar remanent magnetization on both flanks (Figure 4), regardless of the thickness of the sedimentary sequence deposited on top the oceanic crust. This similarity is due to their high blocking temperature range, which prevents any significant thermal demagnetization. Nevertheless, the resultant magnetic anomalies predicted for these two layers show significant differences with lower amplitudes and higher attenuation of the short-wavelength signal predicted for the South American flank compared to the African flank (Figure 4). These differences reflect the contrasting depths of the sheeted dikes and gabbros, which are, due to the different cumulative water depths and sediment thicknesses (Figure 1), generally 3 km deeper on the South American flank than on the African flank.

Contrasting differences in the magnetization states of the two flanks are predicted for the basalts, where the magnetic carrier (titanomagnetite) is highly sensitive to the higher temperatures induced by sedimentation. When using the low range of blocking temperatures (100 to 300 °C; Figures 4c and 4d) for the extrusive basalt, the early Cretaceous remanent magnetization of the South American flank is entirely erased and therefore produces no sea surface magnetic anomaly. A similar effect is also observed on the African flank, although at a less developed stage; hence, small amplitude (~20 nT) short-wavelength surface anomalies arise from the extrusive basalt magnetization. When using a higher blocking temperature range (200 to 400 °C; Figures 4e and 4f) for the extrusive basalts, the magnetization of the South American basalts is only partially erased, whereas that of the African ones remains almost intact. Combined with the effect of the different depths to these source layers, the resulting surface anomalies of the African flank are significantly stronger and less attenuated than those of the South American flank.

3. Discussion

Our coupled thermomagnetic models indicate that post-accretion sedimentation might strongly attenuate, under certain conditions, the magnetization of the upper part of the oceanic crust. This effect is governed by the thickness of the sedimentary sequence and modulated by the blocking temperatures of the basalts (Figure 4). The magnetic observations from the South Atlantic early Cretaceous crust (Figures 1 and 2) reveal that the short-wavelength (15 to 30 km) anomaly content is almost entirely missing in most of the South American profiles, and in some profiles, mostly in the African profiles, this signal is strongly subdued. The thermomagnetic models show that indeed the short-wavelength signal is reduced (for blocking temperatures of 200–400 °C) or eliminated (for blocking temperatures of 100–300 °C). The variable short-wavelength content observed along the different magnetic profiles of the South Atlantic (Figures 1–3) may reflect along-axis variations in the titanium content within the lavas (Lattard et al., 2006) in relation to varying degree of fractionation, or a more complex three-dimensional thermal structure at the ridge axis and its subsequent evolution (Gac et al., 2003, 2006), both probably related to ridge segmentation.

As a consequence, the interpretation of marine magnetic anomalies found near passive continental margins, where the crust is commonly covered by a thick sedimentary pile (>~3 km), should be made with special caution. There, the remanent magnetization of crust that formed during short-lived periods of stable geomagnetic polarity (i.e., chrons) may have been partially, or fully, erased, leading to subdued (or missing) short-wavelength magnetic anomalies. Passive continental margins covered by abundant sediments, such as the edges of the North Atlantic (Bronner et al., 2011), eastern Mediterranean (Granot, 2016), and Australian-Antarctic Basin (Tikku & Cande, 1999), commonly reveal abnormally long-wavelength lineated anomalies. The lack of short-wavelength anomalies there could be attributed to synrifting sedimentation (Levi & Riddihough, 1986), to ultraslow spreading rates or to the post-accretion sedimentation shown here. In any case, these magnetic observations have contributed to ambiguities in the interpretation of the nature of the crust (i.e., continental, transitional, or oceanic; Eagles et al., 2015). Our results indicate that the lack of short-wavelength anomalies may in fact be attributed to thermal demagnetization and therefore that the nature of the crust underlying some of these anomalies may well be oceanic.

Finally, the diminution or complete removal of thermoremanent magnetization in the extrusive basalt heighten the relative contribution of the deeper magnetic layers, affecting not only the amplitude and the short-wavelength content of the anomalies but also their anomalous skewness (e.g., Cande, 1976; Dyment et al., 1994), therefore compromising the possibility to use these magnetic anomalies to determine paleomagnetic poles (e.g., Koivisto et al., 2011; Schouten & Cande, 1976). Furthermore, the altered magnetic anomalies affect the picking location of the polarity reversals on the sea surface magnetic anomalies, which are further offset outward from the ridge axis compared to their location if the original remanent magnetization of the extrusive basalt had been preserved. This effect adds to the outward displacement observed on magnetic anomalies worldwide (DeMets & Wilson, 2008), which mostly results from the different geometry and relative contribution of the lower and upper crustal magnetized layers and may partly explain the large variation of this parameter among ocean basin (DeMets & Wilson, 2008). For the South Atlantic crust (half spreading rate of 25 km/Myr), our model predicts up to 30 km of outward offset in the location of the Mesozoic magnetic anomaly picks. Inclusion of such isochrons in the calculation of plate kinematic models could result in false elevated spreading rates and mislocation of the rotation poles.

4. Conclusions

New thermomagnetic forward models that account for the post-accretion sedimentation history have been used to explain the subdued marine magnetic anomalies observed in the southern South Atlantic early Cretaceous flanks. The results indicate that, for crust underlying thick sedimentary sequences, the original magnetization of the extrusive basalt is being eroded, either partly or entirely, leading to the disappearance of the short-wavelength content, reduction in the amplitude and modification of the shape of the sea surface magnetic anomalies. This effect should be taken into account when interpreting marine magnetic anomalies across passive margins and other areas covered by thick sedimentary sequences, commonly used to infer the nature of the crust, to locate paleomagnetic poles, and to calculate plate kinematic models.

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