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[1] A long standing question in geomagnetism is whether the time variation of the induced crustal field is a detectable quantity and, if so, at which spatial wavelengths. We tackle this problem with the help of a forward modeling approach using a vertically integrated susceptibility (VIS) grid of the Earth's crust. For spherical harmonic degrees 15–90, we estimate the root mean square of the crustal magnetic field secular variation to amount 0.06–0.12 nT/yr at the terrestrial surface between epochs 1960–2002.5. The geographical distribution of the signal shows absolute values reaching 0.65–1.30 nT/yr over South America. Unfortunately, most of the world magnetic observatories currently lie on quasi-stationary features where the crustal field signal variations are expected to be very low. However, this long sought signal could be detected over well chosen regions, provided that satellite, observatory, and repeat station measurements are available over several decades. **Citation:** Thébault, E., K. Hemant, G. Hulot, and N. Olsen (2009), On the geographical distribution of induced time-varying crustal magnetic fields, *Geophys. Res. Lett.*, *36*, L01307, doi:10.1029/2008GL036416.

1. Introduction

[2] The magnetic field of the Earth is a superposition of various internal and external field contributions varying in space and time. In its generally accepted definition, a magnetic anomaly is a field that remains after subtracting known sources such as the main field from the core, and ionospheric and magnetospheric fields. Anomaly fields are thus commonly identified with unmodelled components of the crustal field usually assumed to be static [e.g., *Reeves and Korhonen*, 2008]. In the same way, the concept of secular variation (SV) anomalies has been introduced to describe possible unmodelled field variations that would occur over years. However, this concept is broad because SV anomalies may be caused by any long term geodynamic phenomena occurring in the Earth's core or crust [e.g., *Rossignol*, 1982], if not the upper mantle, the ionosphere, or the magnetosphere.

[3] Among possible crustal geological causes of SV anomalies, piezomagnetism in tectonically active regions [*Johnston et al.*, 1976; *Galdeano et al.*, 1979], over volcanic areas [*Johnston and Stacey*, 1969], or associated with earthquakes [e.g., *Nagata*, 1972] has often been envisioned. Such phenomena are local and would occur under rather specific circumstances. In contrast, core field SV causes induced magnetization and corresponding secondary magnetic fields within the Earth's crust. Quite a few attempts have already been made at isolating such a signal. However, very few publications make an explicit link between possible continental scale SV anomalies and the structure of the crust [*Mundt*, 1990; *Podsklan et al.*, 1993] and more recent regional modeling of observatory and repeat station data, carried out in Europe, were inconclusive in identifying regional SV anomalies [*Korte and Haak*, 2000; *Thébault*, 2008]. Interestingly, investigations at shorter spatial scales have sometimes led to contradictory conclusions [*Lesur and Gubbins*, 2000; *Verbanac et al.*, 2007]. For the time being, SV anomalies are thus still poorly documented in the literature mainly because of a lack of long temporal time series on a dense network of observations. The data coverage in space and, to a lesser extent in time, has improved during the last decade thanks to satellite missions such as Ørsted [*Neubert et al.*, 2001] and CHAMP [*Reigber et al.*, 2002]. The forthcoming ESA Swarm satellite mission [see *Friis-Christensen et al.*, 2006] will continue this successful series of space measurements. However, as discussed by G. Hulot et al. (Crustal concealing of small scale core field secular variation, submitted to *Geophysical Journal International*, 2008), taking advantage of such satellite missions in order to decipher the time varying signal of the crust will likely need several more decades of observations. In this paper, we thus focus on the promising possibilities offered by current, and possible future, magnetic observatories and repeat stations networks at ground level. We rely on a forward model based on known geological properties of the Earth's crust and predict the amplitude and the location of the expected induced crustal SV at the Earth's surface.

2. Prediction of the Time-Varying Crustal Field Anomalies

[4] In this paper, we explore wavelengths between 440 km and 2700 km well detected by low orbiting satellites (altitude 350–550 km). Over continental masses, magnetic anomaly patterns are assumed to be caused by magnetic sources lying in the crust. From the satellite perspective, the Earth's crust is seen as a thin layer of lateral susceptibility variations, and the induced crustal field can be assumed to contribute more to observed magnetic anomalies than continental remanent magnetization. On the basis of the geologic and tectonic maps of the world, susceptibility values of rock types, and the seismic crustal thickness, *Hemant and Maus* [2005a] estimated a vertically integrated susceptibility (VIS) grid of 0.25° × 0.25° resolution. They also computed a remanent magnetization grid with the same resolution for

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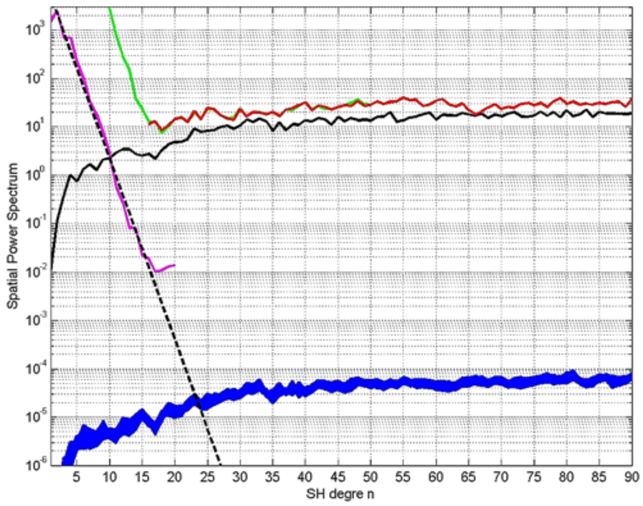

Figure 1. Lowes-Mauersberger spectra (R_n) of xCHAOS for epoch 2004 (green) [*Olsen and Mandea*, 2008], MF6 crustal field model (red) [*Maus et al.*, 2008], and the VIS forward crustal field model (black) [*Hemant and Maus*, 2005a]. Units are in nT^2. Also shown are the SV spectrum (R_n') of xCHAOS for epoch 2004 (pink) with extrapolation (black dashed line) and the predicted lithospheric field SV spectra ($\delta R_n'$) at mid-epochs between 1960.5 and 2001.5 (blue curves). Units are in $(nT/yr)^2$.

the oceanic crust using a digital isochron map of the ocean floor and rotation models of the paleoplates. Using those grids, and a core field contemporaneous of the CHAMP mission, they computed a spherical harmonic (SH) induced crustal field model up to degree 90. The prediction was finally iteratively compared to CHAMP measurements in a way that allowed them to recover an optimized VIS grid. This grid accounts reasonably well for the crustal anomaly field witnessed by CHAMP. We therefore decided to use this VIS grid and to let the inducing core field vary with time between 1960 and 2002.5 (using the core field estimated from the CM4 model [*Sabaka et al.*, 2004]). We then computed each year an estimate of the induced crustal field. Computing the difference between two successive estimates at mid-epochs finally allowed us to estimate the SV produced by the crust.

3. Inherent Uncertainties in the Forward Modeling

[5] The VIS grid results from calculation requiring a priori geophysical and geological knowledge [see *Hemant and Maus*, 2005a], a process which involves some amount of arbitrariness (see *Purucker and Whaler* [2007] for a review). Moreover, it describes the induced part of the crustal field over continents between SH degree 15 to 90, neglecting de facto continental remanent magnetizations (the domination of induced over remanent magnetization was nevertheless tested by *Maus and Haak* [2002]) and contributions between SH degrees 1–14 and above 90. The geology is also poorly known in remote regions and this could lead to a reduction of power at high SH degrees [*Lesur and Maus*, 2006]. Additional uncertainties arise from the CHAMP anomaly model to which the VIS prediction was compared. This model has a power spectrum that is lower than that of models obtained by different strategies. A formal explanation for this discrepancy is given by *Sabaka and Olsen* [2006]. For these reasons, although the VIS magnetic crustal field prediction compares well in shape with CHAMP-based satellite anomaly maps, it underestimates the magnetic field power spectrum by a factor of 3–4 on average (compare black and green curves in Figure 1). Given these uncertainties, our estimation for the time-varying crustal field should mainly be viewed as tentative but represents an interesting low-bound guess of the signal we should expect.

4. Discussion

[6] The Lowes-Mauersberger spectrum of the predicted secular crustal field variation is sketched each mid-year between 1960.5 and 2001.5 in Figure 1 (series of overlapping blue curves). Note that those SV spectra have similar shapes to that of the crustal field. They converge towards $R_n = 10^{-4}$ $(nT/yr)^2$ at the Earth's mean radius and intersect the extrapolated xCHAOS [*Olsen and Mandea*, 2008] core field SV spectrum around SH degrees 23 and 24, depending on the epoch considered. This shows that the core field SV is not expected to contribute significantly to small spatial scale changes beyond degree 24 (which also sets limitations to the investigation of small scale core field SV (see Hulot et al., submitted manuscript, 2008)).

[7] Figure 2 compares the predicted root mean square (RMS) crustal and core fields SV at the Earth's surface between 1960.5 and 2001.5. As might have been expected, the crustal SV RMS follows the core field SV RMS and displays the same inflection points. The intensity is maximum around 1997.5 (0.063 nT/yr), which as already said, is a low estimate. A higher value of 0.12 nT/yr is obtained if one assumes that the VIS crustal field spectrum should be multiplied by a factor of about 4 to reach the level of satellite-based spectra (Figure 1). This, we note, would amount to assuming that all magnetic features detected at satellite altitude are of induced origin. In the following, both possibilities will be considered as a mean to assess the lower and upper limits of the crustal field SV we may expect to

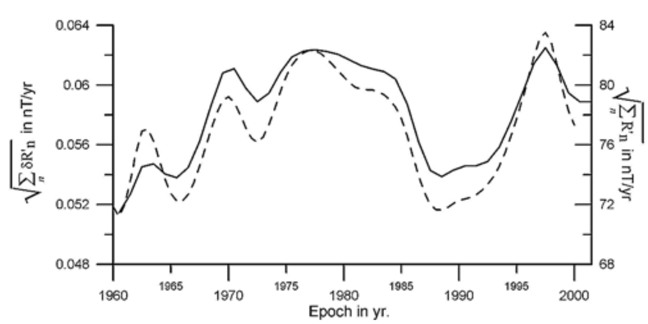

Figure 2. RMS intensity of the crustal field SV (solid line, left ordinate) and the CM4 core field SV model (dashed line, right ordinate) calculated for SH degrees n = 1–90 at the mean Earth's radius in nT/yr every mid-years between 1960.5 and 2001.5.

detect. Other world susceptibility distributions could be used [e.g., *Hahn et al.*, 1984; *Purucker et al.*, 2002], which would likely lead to predictions falling within these bounds. But, because the model of *Hemant and Maus* [2005a] extensively uses various geophysical data and leads to particularly striking correlations between measured and predicted magnetic field features, we consider this model as more appropriate for sketching the spatial distribution of the crustal field changes and, eventually, identifying the regions bearing the highest temporal variation.

[8] Figure 3 presents the worldwide distribution of the crustal field difference between 2002.5 and 1960 predicted at the Earth's mean radius using the VIS technique of *Hemant and Maus* [2005a]. As expected from Figure 1, small spatial scales are particularly prominent. We find absolute maxima of 19–38 nT for X, 17–34 nT for Y, and 23–46 nT for Z over South America. The maximum predicted time variation, close to the Kourou INTERMAGNET observatory, in French Guyana, is 0.65–1.3 nT/yr.

[9] The most significant variations are predicted within the African, the North and the South American continents and their offshore regions. Not surprisingly, this corresponds to the regions of largest core field changes between 1960 and 2002.5 (Figure 3d) and comparatively high crustal VIS [see *Hemant and Maus*, 2005a, Figure 4]. The most significant increase is seen over the continent-ocean (C-O) boundary along north-western and central Africa and along both the eastern and the western continental margins of North and South America. However, no appreciable C-O anomaly is predicted over other continental margins because of the low VIS contrast between oceanic crust and the flanking young continental crust in these regions [*Hemant and Maus*, 2005b]. Oceanic plateaus in the South Atlantic Ocean such as Walvis Ridge, off the coast of Angola (Africa), North Scotia Ridge, off the coast of Falkland Islands,(South America), and Maud Rise, flanking the Greenwich meridian, off the coast of Dronning Maud land (Antarctica) are strikingly prominent. Over the southwest Indian Ocean, off the coast of Africa the Agulhas plateau and the Mozambique Ridge, and further south over the Conrad Rise, the Crozet plateau and the Kerguelen-Gaussberg Ridge show significant changes in the field strength compared to the weak background changing field. Apart from few other regions within the East European Platform, the Indian Subcontinent, and within China, Greenland and Antarctica, no appreciable change in induced field strength is predicted at other locations.

[10] More explicitly focusing on Europe, maximum variations of 0.3–0.6 nT/yr are predicted in the Eastern part but none are expected to exceed 0.1 nT/yr in the Western part. At the considered spatial scale, Western Europe mostly consists of sedimentary rocks that generally have low magnetization while the thicker East European platform has a higher VIS. This susceptibility contrast could induce large crustal field SV. However, Figure 3 shows that changes in the inducing core field were low there between 1960 and 2002.5. For this reason, the sharp and deep character of the suture zone that separates Western from Central Europe does not induce a large spatiotemporal magnetic field variation over this period. This conclusion is in contradiction with the assertions of *Mundt* [1978, 1990], who estimated SV anomalies of crustal origin reaching 7–8 nT/yr over distances of hundreds of kilometers. One plausible explanation for this could be that Mundt considered a dipole SV whereas the core field SV is clearly more complex (Figure 3). Recently, *Verbanac et al.* [2007] argued for significant long-term trend biases reaching 2–5 nT/yr in the Z component in 10 (out of 46) European geomagnetic observatories that could be caused by crustal field induction. The geographical distribution of these trends is however rather erratic and cannot be related to long wavelength crustal field anomalies predicted by our study. Interestingly, by using a different data analysis, *Lesur and Gubbins* [2000] identified 9 (out of 20) European observatories where a time-dependent induced field needs to be invoked to better fit their data. The two studies had 14 observatories in common but only in the case of the Coimbra observatory, in Portugal, did they concur that time-dependent induced field is needed. The VIS prediction shows that Coimbra observatory is close to a predicted local maximum in the Z component.

5. Outlook

[11] The secular crustal field changes we predict in the range n = 15–90 (horizontal wavelength 2700–440 km) are weak. In some regions, however, they can reach levels of the order of 0.65–1.3 nT/yr. Most magnetic observatories unfortunately lie outside those regions. A few isolated observatories, such as Kourou (KOU) in South America, Ottawa (OTT) in North America, or Hartebeesthoek (HBK) in South Africa are nevertheless close to predicted prominent changes. Such signals, of only 0.02 nT/yr at 400 km altitude, cannot be detected from space unless high quality satellite data are available over several decades (see Hulot et al., submitted manuscript, 2008). Substantial advantage could however be taken of such satellite data to build core and large-scale crustal SV models, correct observatory data for this signal, and identify the contribution of medium to small-scale crustal SV at observatory locations. Indeed, core field models similar to xCHAOS, but built with just satellite data (such as the CHAOS model of *Olsen et al.* [2006]) could account for the SV up to about 0.1 nT/yr at ground level (as roughly estimated from the SV spectrum at degree 17 shown in Figure 1), implying that local crustal field variation of 0.65–1.3 nT/yr could potentially be detected.

[12] Identification of SV anomaly spatial gradients with a similar approach is also conceivable but would likely be more challenging because the mean distance between two permanent observatories is currently too large with respect to the length-scales of the largest predicted anomalies. Europe has the densest network but the predicted crustal SV is weak. Additional measurements from repeat stations could also be used. At present, however, the comparatively low quality, the lack of homogeneity of repeat station data, and the regional modeling techniques make it difficult to accurately resolve spatial and time changes. Longer time series and better reduction of repeat station data as well as accurate regional modeling approaches are needed. It is nevertheless quite stimulating to see that, over a period of several decades, the crustal field changes (as shown in Figure 3) can potentially reach such an order of magnitude. With this respect, South Africa could be a good candidate. This part of the continent is monitored by three INTER-

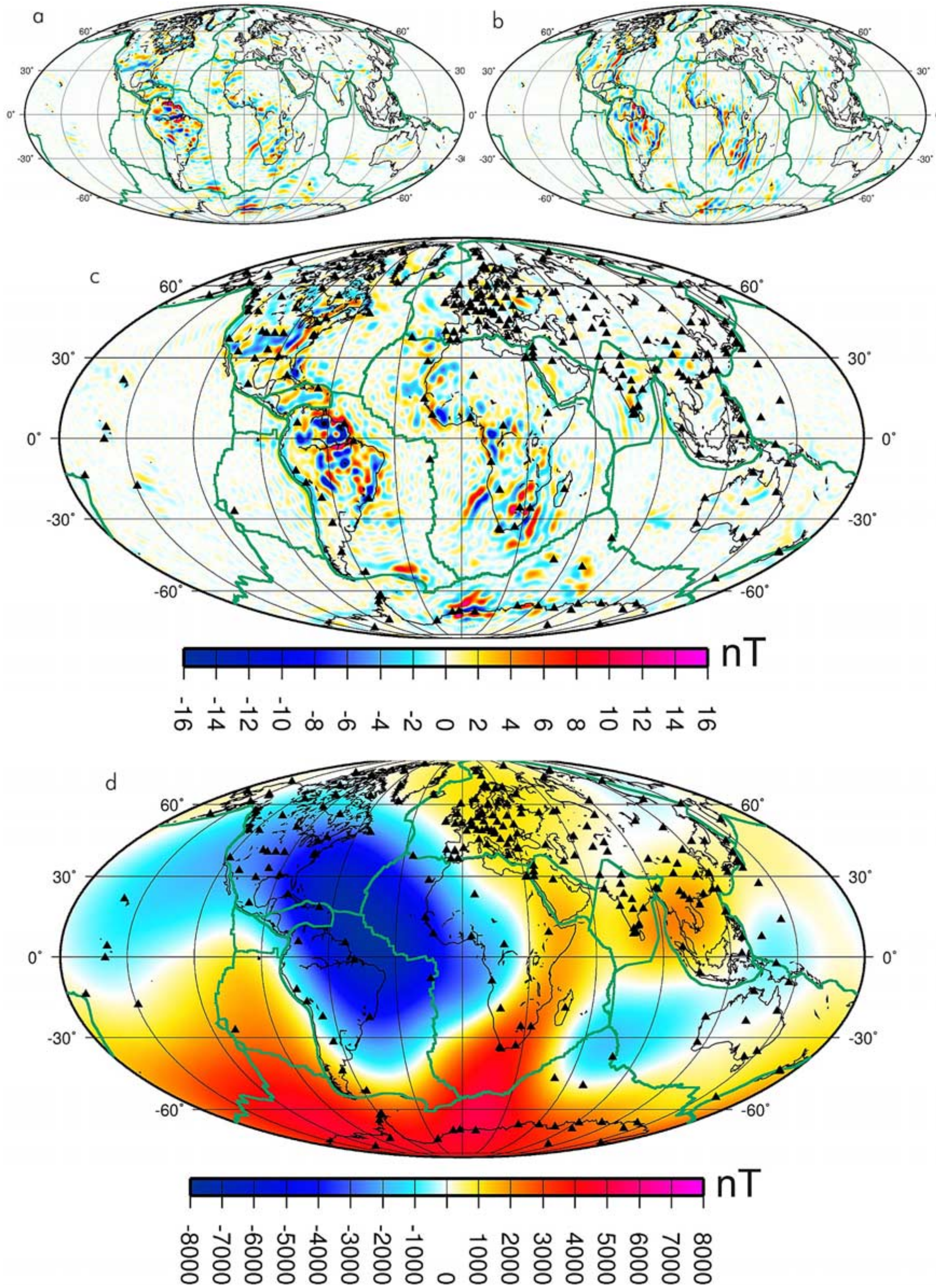

Figure 3. Finite difference between induced crustal magnetic fields calculated at the mean Earth's radius at epochs 2002.5 and 1960.0 in nT: (a) dX, (b) dY, and (c) dZ and (d) the vertical CM4 core field model difference in nT calculated to SH degree 13 between epochs 2002.5 and 1960. Mollweide projection. The low-bound estimate calculated from the VIS grid of *Hemant and Maus* [2005a] is used. Black triangles are world magnetic observatories.

MAGNET observatories (Hermanus and Hartebeesthook, in South Africa, and at Tsumeb, in Namibia) and a network of repeat stations where magnetic measurements are corrected for rapid transient variations [*Korte et al.*, 2007]. Since this is also a place where the crust has a comparatively large VIS and where the inducing core field SV is prominent, detection of SV anomalies might well be achieved in this area in the near future.

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