

Is the Long Wavelength Crustal Magnetic Field Dominated by Induced or by Remanent Magnetisation ?

Stefan Maus and Volker Haak

GFZ-Potsdam, Telegrafenberg, 14473, Potsdam

ABSTRACT

Crustal rocks carry remanent as well as induced magnetisation. In contrast to the remanent magnetisation, the induced magnetisation is aligned with and proportional in strength to the main magnetic field of the Earth. Here, we attempt to identify the nature of the crustal magnetisation by plotting the long wavelength power of the crustal magnetic field against the magnetic dip latitude. For predominantly remanent magnetisation, we expect to see a weak increase in total intensity power with latitude, due to the preferential sampling of the weaker tangential part of the crustal field at the equator and the stronger radial part at the poles. In contrast, a much stronger trend with latitude is expected for induced magnetisation because it is aligned to the main field and increases with its strength towards the poles. The result of our investigation turns out to depend on the crustal field model used in the analysis. Some models show the strong trend with latitude expected for induced magnetisation, while others are consistent with purely remanent magnetisation. We expect that crustal field models from the new Champ satellite data will be able to resolve the issue.

INTRODUCTION

The Earth's crust carries both induced and remanent magnetisation. Remanent magnetisation is strong near the surface and dominates the short wavelength crustal field. Due to the instability of remanence at higher temperatures in the lower crust and upper mantle, the long wavelength crustal field could possibly be dominated by induced magnetisation. Indeed, in the downward continuation and interpretation of satellite magnetic data this assumption is often made.

The Earth's internal magnetic field is around twice as strong at the poles than at the equator. Consequently, any induced magnetisation must increase with latitude, while the strength of remanent magnetisation is likely to be independent of latitude. This unequal behaviour can be utilised to distinguish between induced and remanent contributions to the magnetic field.

Whether the strength of the crustal magnetisation indeed increases with latitude or not is studied here on global crustal magnetic field models. The MAGSAT mission in 1979/1980 demonstrated that it is possible to map the long wavelength crustal field from satellite. Crucial in this respect is a very low orbit altitude of around 400 ~ km. Furthermore, due to the so-called Backus effect, it is necessary to measure the full vector and not only the total intensity of the magnetic field. Measurement of the vector field requires an accurate determination of the instrument orientation, which is provided by star cameras. Since the highly successful MAGSAT mission, the first satellite to measure the magnetic vector field at low altitudes is the German satellite CHAMP, which was launched in July 2000. At this point of time, CHAMP to allow for the

computation of crustal field models has collected not enough high quality data. Therefore, the following analysis shall be restricted to crustal field models based on MAGSAT, POGO and observatory data, namely MO7AV6 (Cain et al. 1989), CMP3 (Sabaca, Olsen & Langel 2000) and ALP94 (Aarkani-Hamed & Dymant 1996). Note that these are magnetic field models and not crustal magnetisation models.

First, we discuss the theoretical strength of the magnetic field total intensity for a latitude independent random remanent magnetisation. Due to a geometric effect, the total intensity power of the crustal field increases by a factor 2 with latitude even if the source magnetisation does not increase with latitude. For induced magnetisation a much stronger increase by a factor $32/3$ from the equator to the poles is to be expected. In the following section, the analysis of crustal field maps is described and results for different models are presented. All field models show a much stronger crustal field over the continents than over the oceans. However, ALP94 is consistent with a purely remanent magnetisation, while MO7AV6 and CMP3 present a strong case for induced magnetisation.

POWER OF THE MAGNETIC FIELD TOTAL INTENSITY

First, let us consider the case of a crust which is magnetised by some random process (random is not synonymous for white noise). The expected strength of the magnetisation in a particular location is assumed to be independent of latitude and independent of the present day main field strength. This situation is illustrated in Fig.1. The anomaly of the total intensity of the magnetic field ΔT is the

contribution of the shorter wavelength crustal field in the direction of the dominant main field. Since the main field is primarily dipolar, ΔT samples the radial component of the crustal field at high latitudes and the tangential component near the equator. A short wavelength poloidal field has half of its power in the radial and only a quarter in each tangential component (Maus 2001), which leads to a dependence of the azimuthally averaged power spectrum P on the inclination I of the main field as in $P \propto 1 + \sin^2 I$. For a dipolar main field this works out to

$$P \propto 1 + 2 \cos^2 \theta (1 + 3 \cos^2 \theta)^{-1/2} \quad (1)$$

where q is the magnetic co-latitude. Hence, ΔT turns out to be twice as strong at the poles than at the equator, even if the source magnetisation is equal.

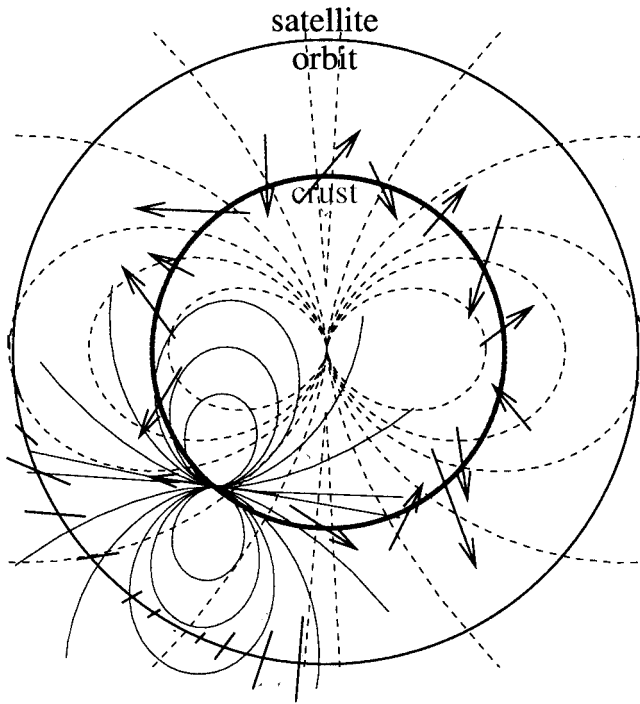


Figure 1. The total intensity at satellite altitude is the component of the crustal magnetic field parallel to the main field lines (dashed). Hence, the total intensity samples the radial component of the crustal field at the poles and the tangential component at the equator. Since the radial component of a high order poloidal field is stronger than each of the two tangential components, the total intensity anomaly increases with latitude for purely geometrical reasons.

For the induced case, consider a random (e.g. self-similar) distribution of susceptibility in the crust. Then the 2D power spectrum P^{2D} of ΔT depends on the direction and

strength of the inducing field (Maus, Gordon & Fairhead 1997}, as in

$$P^{2D}(\alpha) \propto F^2 (Z^2 + H^2 \cos^2 \alpha)^2, \quad (2)$$

where F is the total intensity, Z is the vertical component, and H is the intensity of the horizontal component of the inducing main field. Finally, α is the azimuth, with $\alpha = 0$ for the northward direction. Note that this dependency is valid for any wave number k . Here, we are not interested in azimuthal differences. We therefore consider the azimuthally averaged (“radial”) power spectrum

$$P = \frac{1}{\pi} \int_0^\pi P^{2D}(\alpha) d\alpha \quad (3)$$

With eq. (2), for any crustal field wavenumber, this radial power spectrum is proportional to:

$$P \propto \frac{2}{\pi} \int_0^{\pi/2} F^2 (Z^2 + H^2 \cos^2 \alpha)^2 d\alpha \quad (4)$$

$$\propto F^2 (Z^4 + Z^2 H^2 + \frac{3}{8} H^4). \quad (5)$$

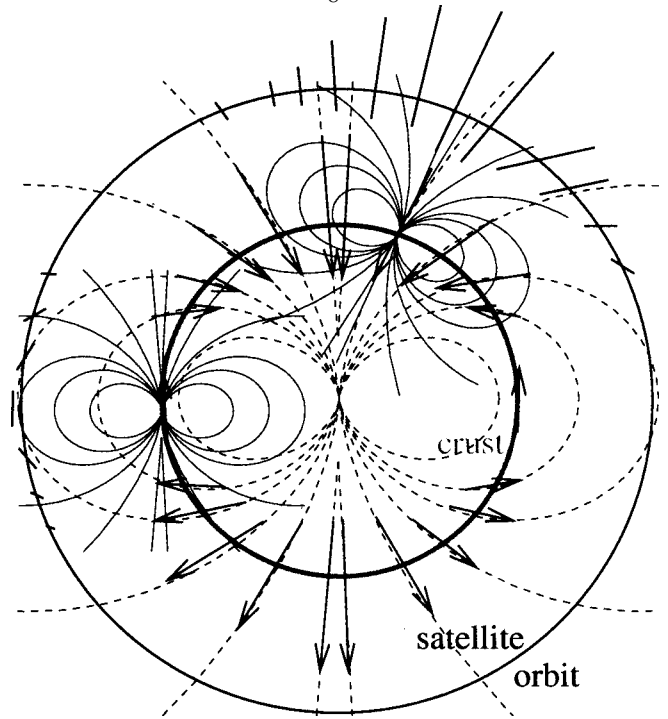


Figure 2. Induced magnetisation produces a total field anomaly with a stronger latitudinal increase for two reasons: First of all the strength of the inducing field increases with latitude and so does the induced magnetisation. Furthermore, the magnetisation is aligned with the inducing field. Thus, the induced crustal dipoles point their strong polar field towards the observer at the poles and their weak equatorial field towards the observer at the equator.

A dipolar main field has a dependence on the magnetic co-latitude θ , which is given by

$$F^2 = N^2 (1 + 3 \cos^2 \theta) \quad (6)$$

$$Z^2 = 4N^2 \cos^2 \theta \quad (7)$$

$$H^2 = N^2 \sin^2 \theta, \quad (8)$$

where N is the strength of the main field at the equator. Inserting these terms into (5) gives the co-latitude dependence of the total field power due to a dipolar-inducing field as:

$$P \propto \frac{32 \cos^2 \theta + 96 \cos^4 \theta + 3 \sin^4 \theta}{3 (1 + 3 \cos^2 \theta)} \quad (9)$$

where the constant factor N^2 has been dropped. In particular, this gives a value of 1 at the equator ($\theta = 90^\circ$), relative to $32/3$ at the poles. Hence, ΔT power due to induced crustal magnetisation increases by more than a factor 10 from the equator to the poles, while the power of the inducing field increases by only a factor 4. This additional increase is due to a geometric effect, namely, that the induced dipoles are pointing their weak side towards the observer at the equator and their strong side towards the observer at the poles. This effect is illustrated in Fig.2.

RESULTS

In the following analysis we use three crustal field models, ALP94 (Arkani-Hamed, Langel & Purucker 1994), MO7AV6 (Cain et al. 1989) and CMP3 (Sabaca, Olsen & Langel 2000). ALP94 has been computed by a cross-correlation procedure from along-track filtered POGO and MAGSAT total field data. No vector data was used. MO7AV6 and CMP3 are derived from MAGSAT vector

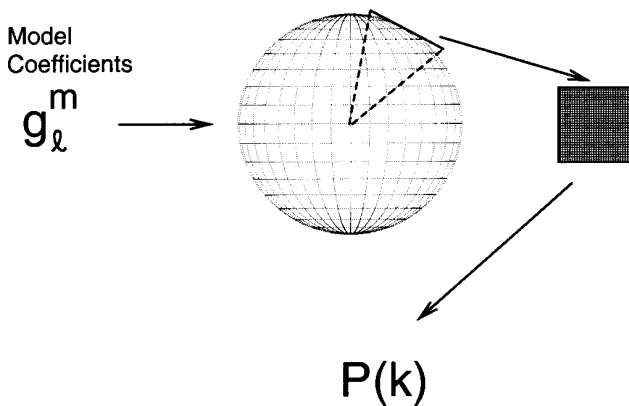


Figure 3. Magnetic field values are computed from the spherical harmonic coefficients of a global field model and are then projected onto tangential grids at satellite altitude. The plane power spectra of the grids are then estimated by the FFT method.

data. MO7AV6 employs observatory vector data to reduce ionosphere contributions. CMP3 is the latest version in a series of fully comprehensive models, in the sense that it attempts to describe the full time variability of the magnetic field, including main field, lithospheric field, the time-varying ionospheric and magnetospheric contributions (plus their induced counterparts in the Earth's mantle), and the toroidal magnetic field produced by currents at satellite altitude. In addition to the Magsat vector data, POGO total field and observatory vector data were used in deriving CMP3. Here, we only analyse the constant crustal field portion of CMP3.

To arrive at an approximately equal distribution of sample grids on the sphere, we project a cubic mesh onto a spherical surface at 400 km altitude and compute the magnetic field for a tangential sample grid of approximately 2400 km by 2400 km for every knot position (Fig.3). Subsequently, grids with more than 90 % ocean are classified as ocean, less than 40 % ocean as continent and the rest is rejected. See Fig.4 for the distribution of grid locations. Then we estimate the azimuthally averaged power spectra by the usual FFT technique and plot the power in the second overtone, corresponding to wavelengths of around 1200 km, as a function of the magnetic dip latitude. This procedure is repeated for each of the crustal field models and the results are given in Figs 5 to 7.

The results for ALP94 (Fig.5) turn out to be rather consistent with a latitude independent remanent crustal magnetisation. This is noteworthy because this model has been employed in studies inverting the crustal magnetic field for the susceptibility of an induced magnetisation (Arkani-Hamed & Hamed & Dyment 1996; Purucker et al. 1998). However, the ALP94 crustal field model motivates the opposite conclusion, since it does not show a strong enough increase in field power with latitude to make a case for induced magnetisation, in particular over the oceans. In contrast, model MO7AV6 (Fig.6) indicates a very strong increase in crustal field strength towards high

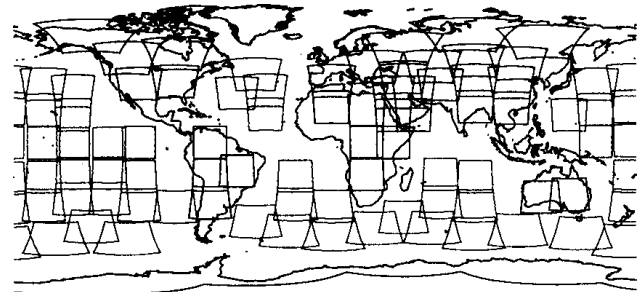


Figure 4. From 1536 plane grids, those with more than 90 % ocean were chosen as ocean samples and those with less than 40 % ocean as land samples. Displayed here is only 1 out of every 9 grids.

latitudes. For magnetic dip latitudes above 60° there is a high uncertainty in crustal field strength due to disturbance of the magnetic field by auroral ionospheric currents. However, for lower latitudes the trend is very clear and follows closely the prediction for purely induced magnetisation. The result for CMP3 (Fig.7) lies in between the results for MO7AV6 and ALP94, with a strong trend over the continents and a weaker trend over the oceans.

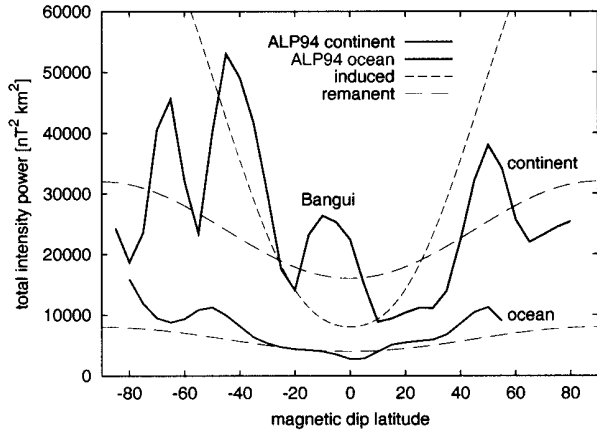


Figure 5. Power of the crustal field total intensity at ≈ 1200 km wavelength, as given by model ALP94 at 400 km satellite altitude. The lump in the continent curve at -10° magnetic latitude is caused by the exceptionally strong African Bangui anomaly. Model curves illustrate the expected geometry effect for a latitude independent remanent magnetisation (eq.1) and the latitude dependence expected for purely induced magnetisation eq. (9). The former provides a better fit to the observed strength of the field over the oceans. For the continents, both trends appear possible.

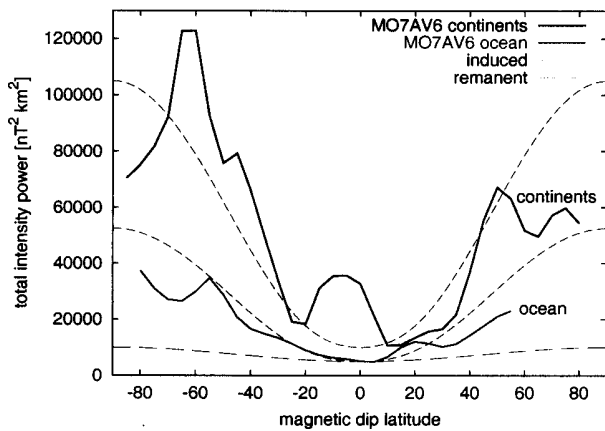


Figure 6. Same as Fig 5. but for model MO7AV6. In this case, the strength of the field over ocean and land is close to the expected trend for induced magnetisation.

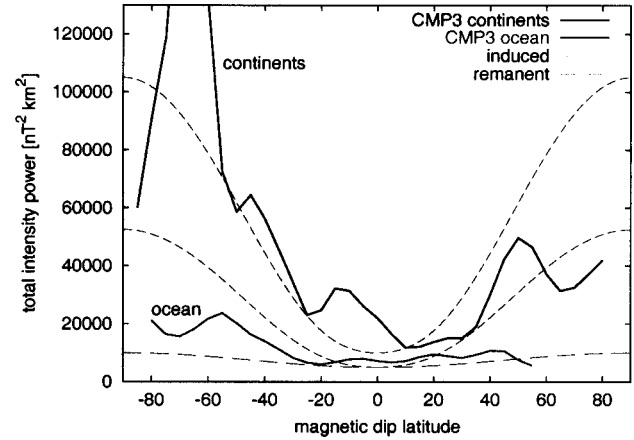


Figure 7. Same as Fig. 5 but for model CMP3. As with MO7AV6, the strength of the field is more compatible with induced magnetisation than with remanent magnetisation.

Discussion

In this study we have investigated whether the strength of the crustal magnetisation increases with latitude. According to the two crustal field models MO7AV6 and CMP3, the field behaves approximately as expected for an induced crustal magnetisation. In contrast, model ALP94 suggests that the magnetisation is primarily remanent and hardly increases with latitude. It is expected that improved crustal models from the new Champ satellite data will clarify the issue. An interesting idea for the future, motivated by this study, is that one could use the theoretical latitude dependence of the crustal field strength for remanent or induced magnetisation, given by eqs. (1) and (9), as *a priori* information in the modelling of high latitude satellite magnetic data. This may provide a useful constraint in dealing with the difficult contamination of satellite data by auroral ionospheric current systems.

REFERENCES

- Arkani-Hamed, J. & Dymert, J., 1996. Magnetic potential and magnetisation contrasts of the earth's lithosphere, *J. Geophys. Res.*, 101, 11,401-11,425.
- Arkani-Hamed, J., Langel, R.A. & Purucker, M., 1994. Scalar magnetic anomaly maps of earth derived from POGO and Magsat data, *J. Geophys. Res.*, 99, 24,075-24,090.
- Cain, J.C., Want, Z., Kluth, C. & Schmitz, D.R., 1989. Derivation of a geomagnetic model to $n = 63$, *Geophys. J. Int.*, 97, 431-441
- Maus, S., 2001. New statistical methods in gravity and magnetics, Habilitation thesis, University of Braunschweig, <http://www.gwdg.de/~smaus/habil.pdf>.

Maus, S., Gordon, D. & Fairhead, J.D., 1997. Curie-temperature depth estimation using A self similar magnetization model, *Geophys. J. Int.*, 129, 123-168.
Purucker, M.E., Langel, R.A., Rajaram, M. & Raymond, C., 1998. Global magnetization Models with a priori

information, *J. Geophys. Res.*, 103, 2563-2584.
Sabaka, T.J., Oslen, N. & Langel, R.A., 2000. A comprehensive model of the near-Earth Magnetic field : phase 3, Technical Report, pp. 75, NASA/TM-2000-209894.

(Accepted 2001 July 30. Received 2001 June 29; in original form 2000 December 21)