ANNALI DI GEOFISICA, VOL. 42, N. 2, April 1999

Satellite magnetic anomalies of the Antarctic crust

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Abstract
Spatially and temporally static crustal magnetic anomalies are contaminated by static core field effects above spherical harmonic degree 12 and dynamic, large-amplitude external fields. To extract crustal magnetic anomalies from the measurements of NASA's Magsat mission, we separate crustal signals from both core and external field effects. In particular, we define Magsat anomalies relative to the degree 11 field and use spectral correlation theory to reduce them for external field effects. We obtain a model of Antarctic crustal thickness by comparing the region's terrain gravity effects to free-air gravity anomalies derived from the Earth Gravity Model 1996 (EGM96). To separate core and crustal magnetic effects, we obtain the pseudo-magnetic effect of the crustal thickness variations from their gravity effect via Poisson's theorem for correlative potentials. We compare the pseudo-magnetic effect of the crustal thickness variations to field differences between degrees 11 and 13 by spectral correlation analysis. We thus identify and remove possible residual core field effects in the Magsat anomalies relative to the degree 11 core field. The resultant anomalies reflect possible Antarctic contrasts due both to crustal thickness and intracrustal variations of magnetization. In addition, they provide important constraints on the geologic interpretation of aeromagnetic survey data, such as are available for the Weddell Province. These crustal anomalies also may be used to correct for long wavelength errors in regional compilations of near-surface magnetic survey data. However, the validity of these applications is limited by the poor quality of the Antarctic Magsat data that were obtained during austral Summer and Fall when south polar external field activity was maximum. Hence an important test and supplement for the Antarctic crustal Magsat anomaly map will be provided by the data from the recently launched Ørsted mission, which will yield coverage over austral Winter and Spring periods when external field activity is minimal.

Key words *Antarctic – crust – magnetic anomalies – ADMAP – satellite surveys – airborne surveys*

1. Introduction

Satellite magnetometer observations collected by NASA's earth-orbiting missions (*i.e.*, POGO and Magsat) provide significant constraints for understanding regional petrological variations of the crust and upper mantle, and crustal thickness and thermal perturbations (*e.g.*, von Frese *et al.*, 1982; Mayhew, 1985; Langel, 1990; Purucker *et al.*, 1999). These sun-synchronous, polar-orbiting satellites have obtained especially dense coverage of the polar regions up to about 83° latitude. Hence, satellite magnetic data represent an important augmentation to near-surface surveys for geological studies of the poorly mapped and understood polar regions.

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In general, crustal sources of satellite magnetic anomalies can have both inductive and remanent components of magnetization. These sources may be predominantly in the lower crust that is believed to be substantially more magnetic than the upper crust (Wasilewski *et al.*, 1979; Wasilewski and Mayhew, 1982, 1992; Mayhew *et al.*, 1985). As crustal depth increases, conditions for coherent inductive regional magnetization are enhanced. Remanence and thermal overprints are diminished, and viscous magnetization and initial susceptibility are enhanced as temperatures increase to within about 100-150 °C of the Curie point of magnetite (≈ 570 °C). The thickness of the crust in this thermal regime of the Curie point may be 5 to 20 km depending on the steepness of the geothermal gradient.

Accordingly, deep crustal magnetic sources are probably related to Curie isotherm topography and lateral variations of petrologic factors. Viscous remanent magnetization in the lower crust is in-phase with the induced component. Hence satellite magnetic anomalies due to lower crustal sources have geometries that may be treated effectively in the context of induced magnetization. Errors in using the assumption of induced magnetization will be confined mostly to interpreting the magnetization intensities for these satellite anomaly sources.

Within the relatively weaker magnetic upper crust, remanently magnetized sources tend to produce high frequency signals that are substantially attenuated at satellite altitudes. Possible exceptions are the Cretaceous quiet zones that can involve large areas of remanently magnetized, normal polarity oceanic crust (LeBrecque and Raymond, 1985). However, their occurrence within the study region is limited and their remanent components are also predominantly in-phase with inductive magnetization. Hence upper crustal sources of satellite magnetic anomalies may also be treated effectively in the context of induced magnetization.

Satellite magnetic data can also be important for improving regional or global compilations of near-surface magnetic surveys. Long wavelength anomalies from these compilations are often seriously corrupted due to gaps in data coverage and errors in data leveling and correcting for secular core field variations (*e.g.*, Schnetzler *et al.*, 1985; Grauch, 1993; Verhoef *et al.*, 1996). However, such errors can be reduced by the use of satellite magnetic observations because they provide relatively uniform regional coverage and are taken over periods where secular variations of the core field are negligible.

Hence, satellite magnetometer data can facilitate the efforts of the Antarctic Digital Magnetic Anomaly Project (ADMAP) that is working to integrate more than one million line kilometers of near-surface magnetic survey data into a magnetic anomaly map for the Antarctic (Johnson *et al.*, 1996, 1997). In particular, Antarctic satellite magnetic observations can be used to develop a geologically coherent reference anomaly field to help augment gaps in coverage and improve the merger of disparate near-surface surveys into regional- and continental-scale composite compilations where the spectral properties of the magnetic anomalies of the south polar lithosphere are developed as fully as possible.

Applications of the Antarctic satellite magnetic data such as described above require effective separation of lithospheric components from the core and external field components. In the sections that follow, we consider specifically the problems of extracting the crustal components from the Antarctic Magsat data and merging these components with near-surface magnetic survey data.

2. Estimating crustal components from regional magnetic observations

Satellite-altitude geomagnetic field observations include core, lithospheric, and external field components along with measurement error. Core field variations range from about 20000 nT near the geomagnetic equator to more than 60000 nT at the poles, whereas external field effects vary typically between ± 200 nT. Lithospheric signals by contrast are relatively weak, ranging commonly between ± 20 nT. Measurement error is about 3 nT for the Magsat scalar anomaly values (Langel, 1990) that are considered in this study. Hence, ignoring instrument noise, a satellite magnetometer observation includes a core field contribution of roughly 97.8%

or more, an external field component of nearly 2% or less, and a lithospheric component of only about 0.2% or less.

Errors in estimating lithospheric anomalies are derived predominantly from errors in the core field model (Alsdorf *et al.*, 1994). Errors in the core field model and lithospheric anomaly estimates are especially exacerbated in the polar regions, where the raw data are contaminated by highly dynamic external fields from auroral electrojets, field-aligned currents and large-scale ring currents. Hence estimating lithospheric anomalies from satellite magnetic observations is quite difficult because the core and external fields cannot be modeled with sufficient accuracy to extract these relatively weak signals.

Presently, effective separation of the polar anomaly fields is best approached as a statistical problem that exploits the coherent or static properties of lithospheric anomalies (Alsdorf *et al.*, 1994) and the core field. This approach involves the use of spectral correlation theory (von Frese *et al.*, 1997) for differentiating these components from the spatially and temporally dynamic effects of the polar external fields.

To illustrate this approach, an example for the Antarctic Magsat data is considered that was developed in support of the near-surface magnetic survey compilation efforts of ADMAP. Figure 1 outlines the processing efforts that were implemented to reduce the Magsat observations for their crustal anomaly components. Initial efforts identify the orbital tracks across the study area. These data are then screened for obvious measurement errors, despiked, reformatted from time to spatial coordinates, and geographically sorted (Alsdorf *et al.*, 1994; Alsdorf and von Frese, 1994; Kim, 1996).

Efforts focus next on isolating the external fields by wavenumber correlation filtering of immediately adjacent passes and the further filtering of maps at varying local times (Alsdorf *et al.*, 1994). These passes are reduced for core field components to degree 11 because the lower degree components tend to be minimally contaminated by the long wavelength magnetic effects of the crust relative to the residual higher (*i.e.*, 12 and 13) degree components (*e.g.*, Langel and Estes, 1985; Meyer *et al.*, 1985; Hinze *et al.*, 1991). Figure 2 shows the geomagnetic field

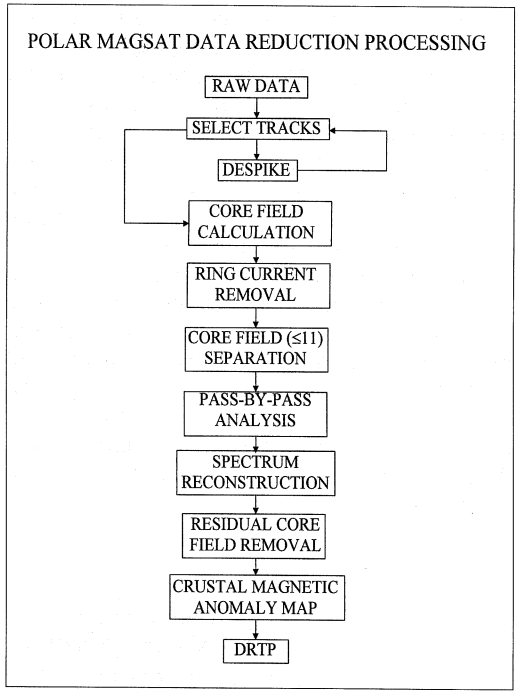

Fig. 1. Generalized data reduction scheme for extracting crustal anomalies from the polar Magsat data.

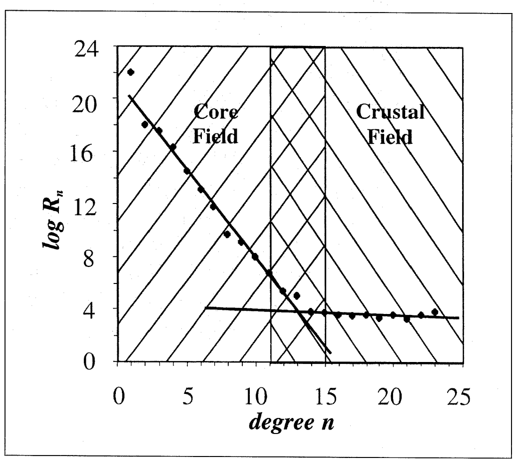

Fig. 2. Logarithmic spectrum of degree n geomagnetic field power (R_n) at the surface of the Earth from Magsat data (adapted from Langel and Estes, 1982). Significant overlap may occur between core field and long wavelength crustal field components between degrees 11 and 15.

spectrum obtained by Langel and Estes (1985) where core field effects are commonly interpreted to be dominant through degree 12 in contrast to lithospheric effects that are felt to predominate at degrees 15 and higher. Separation of core and crustal field effects in the residual components between degrees 11 and 13 is attempted after the satellite magnetic data have been reduced for the dynamic external field effects.

After removing the core field components to degree 11 using the GSFC 12/83 model (Langel and Estes, 1985), the passes are sorted by local time into dawn and dusk data sets, placed into several altitude bins, and arranged geographically for processing by the procedures of Alsdorf *et al.* (1994) to suppress external field effects. The distance between adjacent passes is small compared to the distance to the lithosphere, so that these nearest-neighbor passes should exhibit similar lithospheric and residual core field signals. Hence, pass-to-pass correlation filtering is used to extract the correlative signatures from adjacent passes.

Some polar external fields are coherent across the passes and must be removed by filtering the maps at different local times (Alsdorf *et al.*, 1994). With the Magsat data, the polar external fields are generally asymmetric across the dawn and dusk local times. Therefore, correlation filtering of the local time maps at each altitude results in maps that have reduced effects from external fields.

After averaging the filtered local time maps at the different altitudes, the resultant maps are continued to a common altitude by the Equiva-

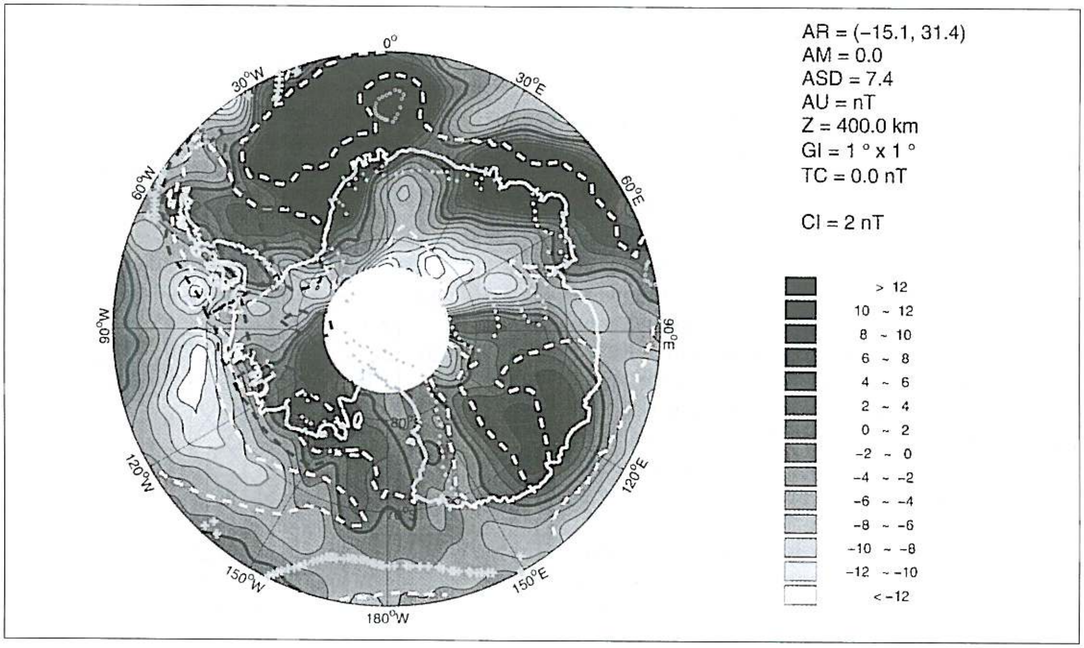

Fig. 3. Antarctic Magsat scalar total field magnetic anomalies relative to the spherical harmonic core field model GSFC 12/83 (Langel and Estes, 1985) at degree 11. Annotations include the Amplitude Range (AR) of (min, max)-amplitudes, the Amplitude Mean (AM), Amplitude Standard Deviation (ASD), Amplitude Unit (AU), and map elevation (Z), Grid Interval (GI), and Contour Interval (CI). Shading and line contours are incremented by the CI. The Thick Contour (TC) delineates the zero amplitude with thin solid and dashed contours delineating amplitudes greater and less than zero, respectively. Generalized geologic features are superimposed, including basins (white dashes), mountains and outcrops (white dots), microplates (black dashes), and oceanic plateaux (white circles) and ridges (pluses).

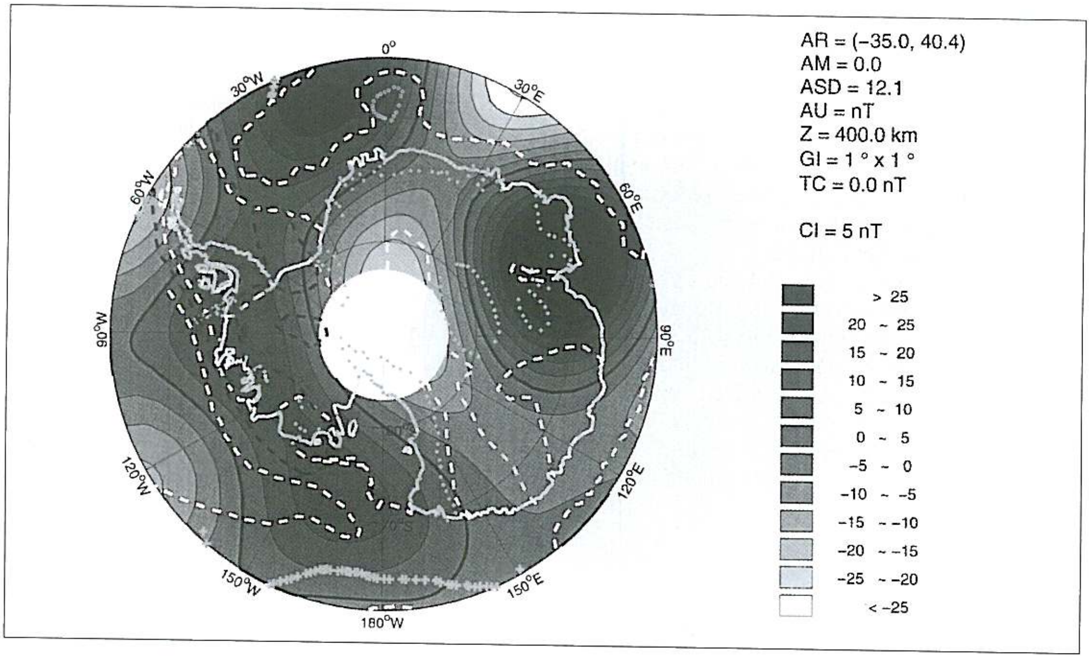

Fig. 4. Intensity differences between degree 13 and degree 11 in the core field model GSFC 12/83 (Langel and Estes, 1985), where the magnetic effects due to crustal thickness variations are presumably strongly intermixed with core field variations.

lent Point Source (EPS) inversion procedures of von Frese *et al.* (1981, 1988, 1998) and again correlation filtered for static anomalies. The filtered results are then averaged together to produce the scalar total field magnetic anomalies of the Antarctic shown in fig. 3.

Efforts focus now on reducing these scalar anomalies for residual core field effects to isolate crustal magnetic anomalies that are related to intracrustal magnetization contrasts and crustal thickness variations. Our interpretation of the geomagnetic spectrum in fig. 2 suggests that core field model components between degrees 11 and 13, which are shown in fig. 4, may be strongly contaminated by the regional magnetic effects of crustal thickness variations. Hence in fig. 3, we presume that these effects are predominantly intermixed in the long wavelength components, whereas the higher frequency components are taken to reflect mostly intracrustal magnetization variations.

Efforts to separate these effects must take into account the sources of crustal magnetization that may be reflected by magnetic anomalies at satellite altitudes. For the Antarctic, remanence is a poorly known, but possibly significant aspect of crustal magnetization. Accordingly, in this study the lithospheric components of satellite magnetic anomalies are based on sources with induced magnetization contrasts. Any remanent components are presumed to introduce errors that are mostly relegated to interpretations of the magnetization intensities while minimally affecting interpretations of the anomaly phase properties. Hence Differentially Reducing to The Pole (DRTP) the satellite magnetic anomalies (von Frese *et al.*, 1981) using EPS inversion may be effective in mapping out lateral magnetization variations in the lithosphere, even though the interpretation of related magnetization intensities may be complicated by the presence of remanence in the deep and shallow crust.

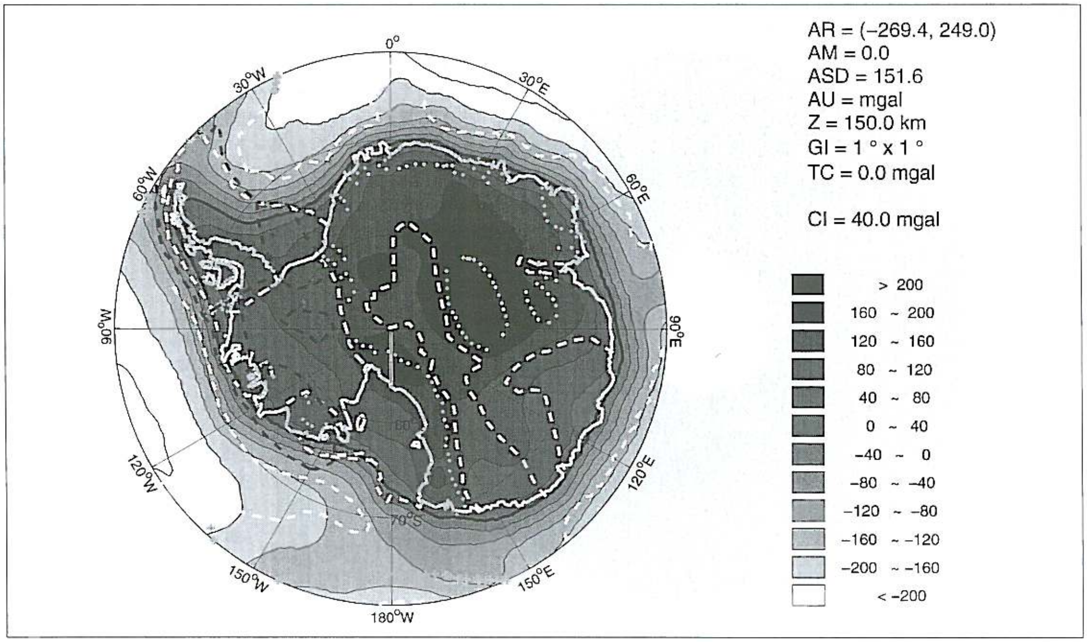

Fig. 5. Compensated terrain gravity effects for the Antarctic (von Frese *et al.*, 1997a).

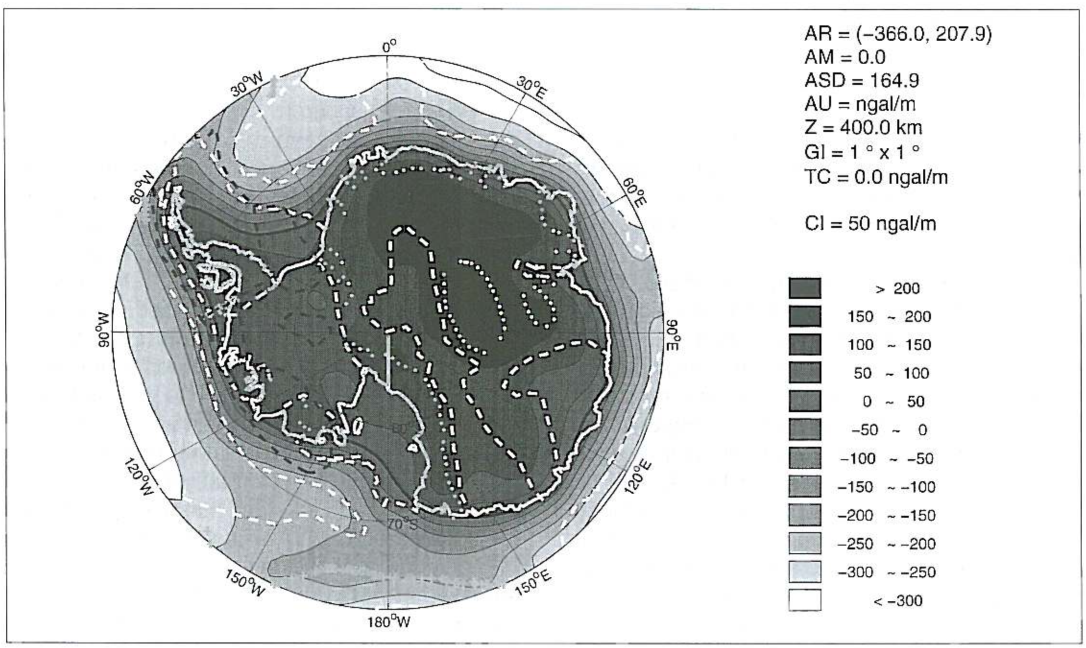

Fig. 6. First vertical derivative anomalies of the compensated terrain gravity effects of the Antarctic.

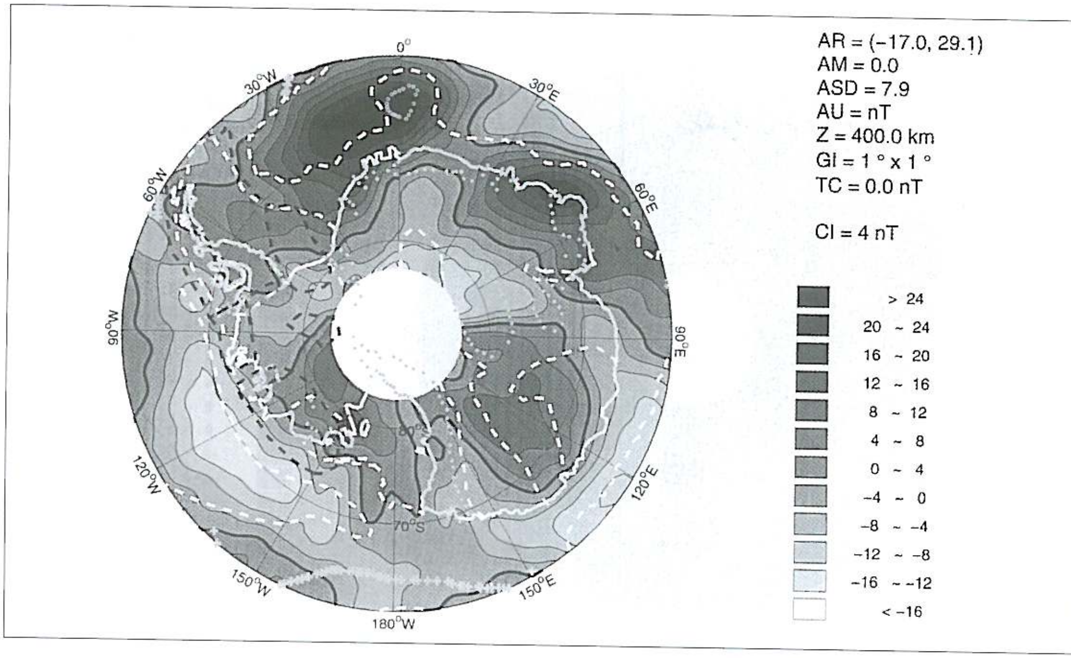

Fig. 7. Differentially Reduced To Pole (DRTP) Antarctic Magsat scalar total field magnetic anomalies relative to the spherical harmonic core field model GSFC 12/83 (Langel and Estes, 1985) at degree 11.

To estimate the effect of crustal thickness variations in the magnetic anomalies, we can convert their gravity effects via Poisson's theorem for correlative potentials (von Frese *et al.*, 1981) into pseudo-magnetic effects that may be compared to the magnetic anomalies in fig. 3 by spectral correlation theory. The coefficient of correlation between two or more features is solely a function of their phase properties (*e.g.*, von Frese *et al.*, 1997b). Hence to estimate the magnetic effect of crustal thickness variations by spectral correlation filtering, we need to obtain the effective phase properties of their pseudo-magnetic effects. These properties may be obtained from the compensated Antarctic terrain gravity effects that were estimated by von Frese *et al.* (1997a) as shown in fig. 5. In particular, Poisson's theorem relates the first vertical (radial) derivative of these gravity effects to their equivalent radially polarized magnetic effects by their magnetization-to-density ratios (von Frese *et al.*, 1982). Figure 6 gives the radial first derivatives of fig. 5 that were obtained by EPS inversion.

EPS inversion was also used to reduce the magnetic anomalies in fig. 3 differentially to the radial pole. Figure 7 shows these results that include the radially polarized magnetic effects of Antarctic crustal thickness variations. The crustal thickness magnetic anomalies were extracted by inversely transforming all wavenumber components of fig. 7 that are positively correlated with the wavenumber components of fig. 6. Figure 8 gives our estimate of the radially polarized magnetic anomalies in the Magsat data caused by crustal thickness variations.

Subtracting fig. 8 from fig. 7 yields the residual components in fig. 9. These features include long wavelength anomalies that may be related to core field components above degree 11 because fig. 9 and the core field differences of fig. 4 are highly correlated (CC = 0.79). To extract the residual core field components between degrees 11 and 13, the anomalies of

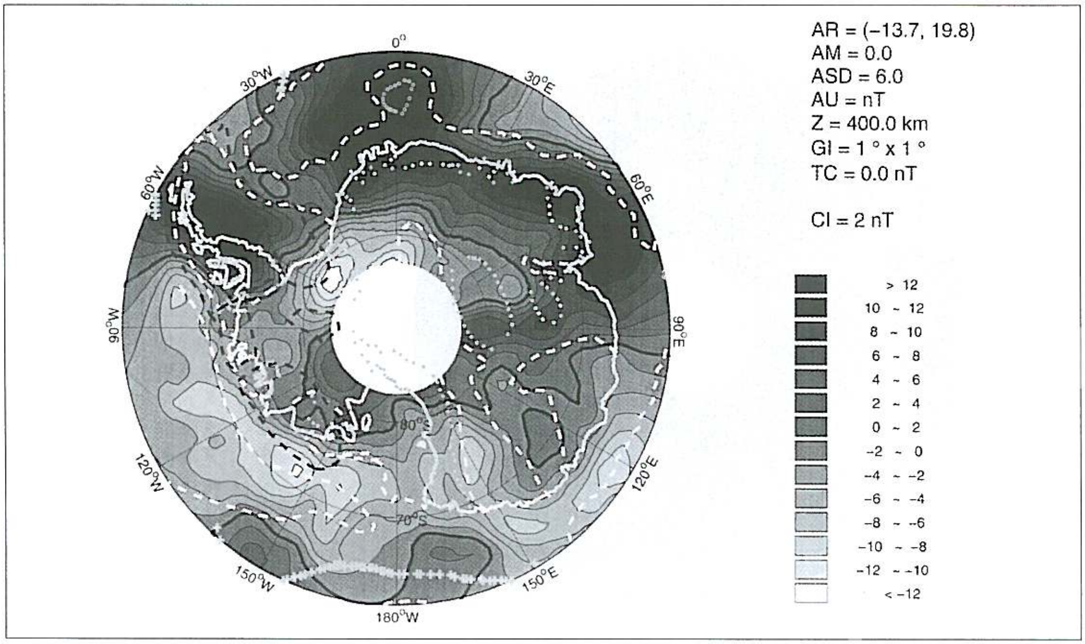

Fig. 8. Antarctic Magsat DRTP-magnetic anomalies from crustal thickness variations.

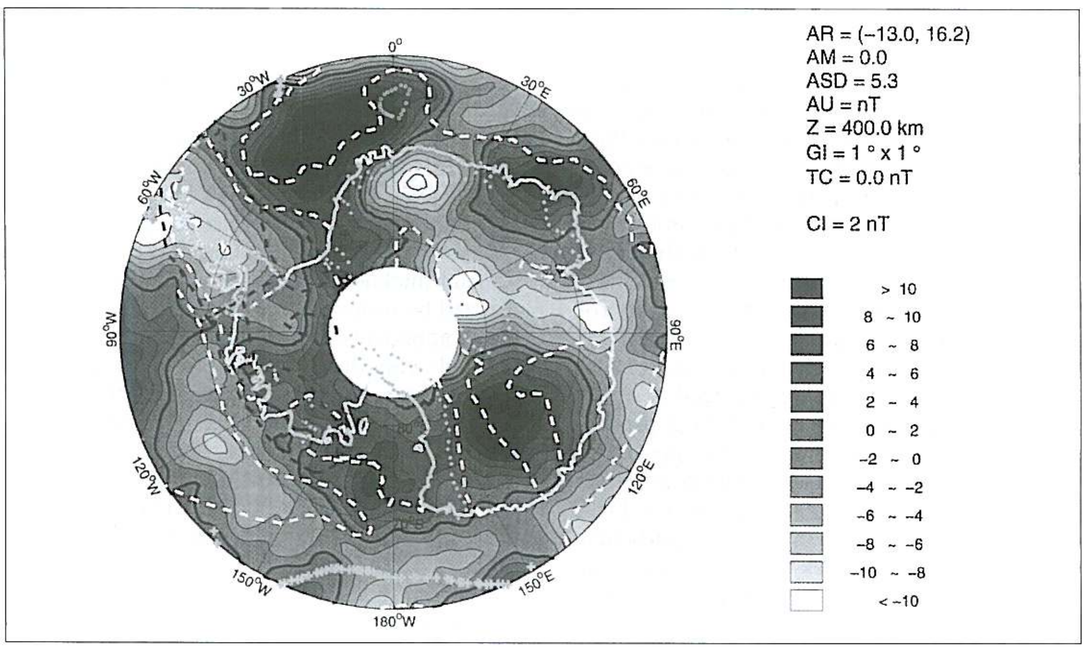

Fig. 9. Antarctic Magsat DRTP-magnetic anomaly differences (figs. 7 - 8).

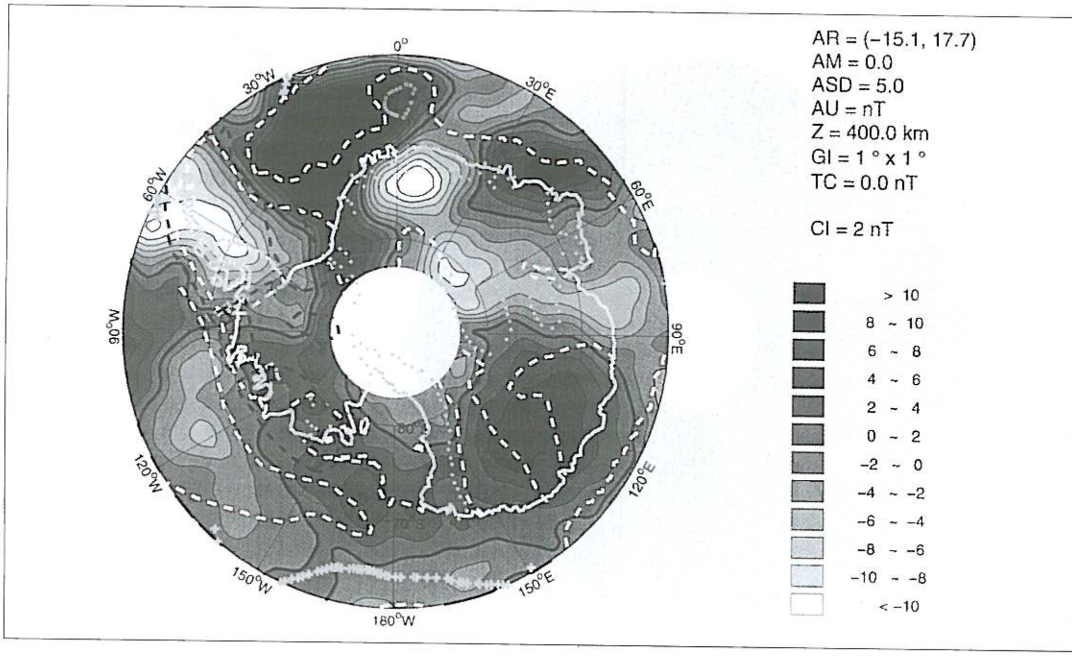

Fig. 10. Antarctic Magsat DRTP-magnetic anomaly differences (figs. 7 - 8) reduced to equivalent scalar total field magnetic anomalies.

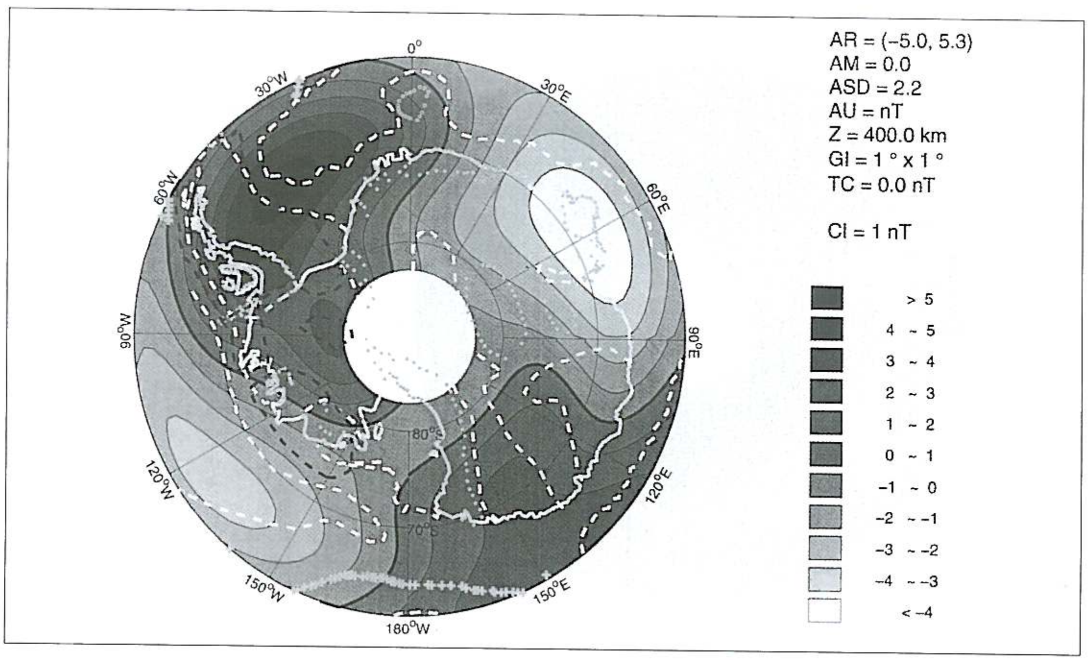

Fig. 11. Residual core field effects in the Antarctic Magsat scalar total field magnetic anomalies (fig. 3).

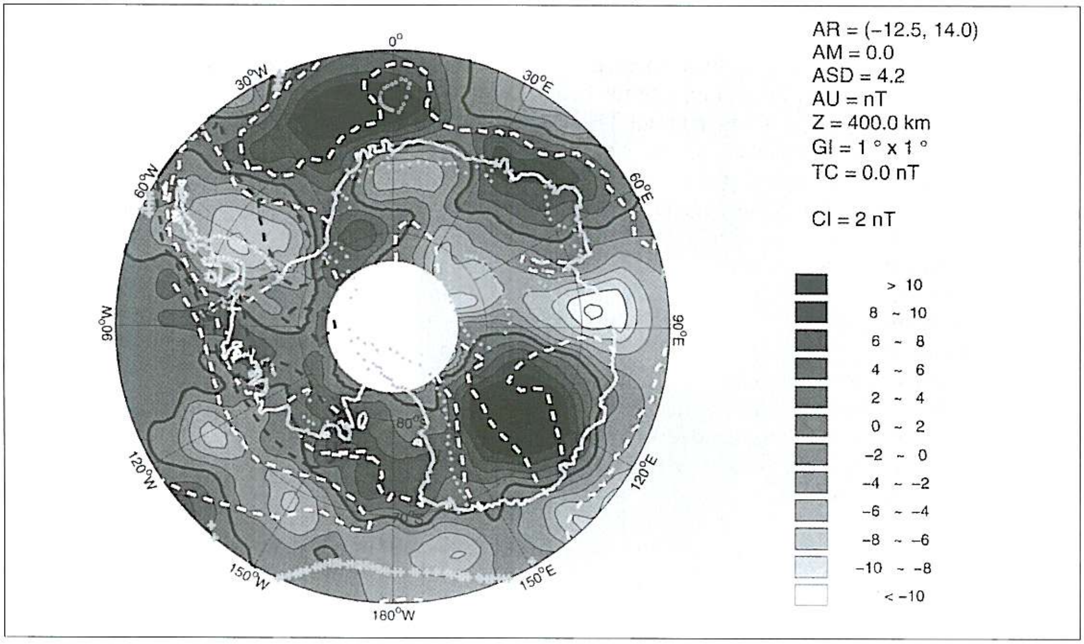

Fig. 12. Antarctic intracrustal Magsat DRTP-magnetic anomalies.

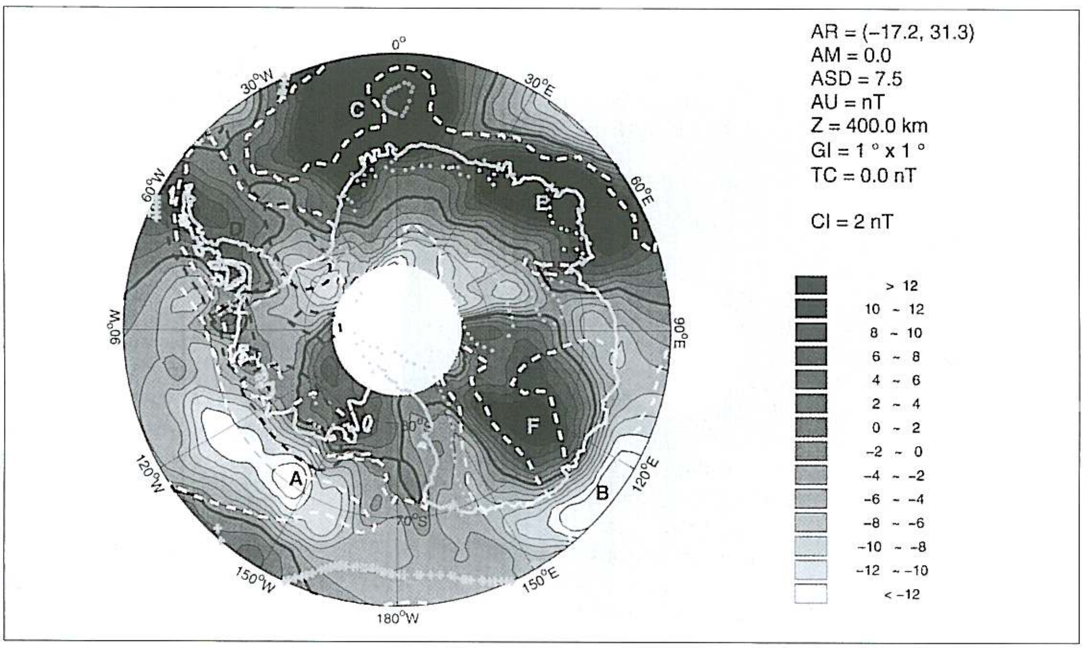

Fig. 13. Antarctic Magsat crustal DRTP-magnetic anomalies. Alphabetically labelled anomaly features are discussed in the text.

fig. 9 were transformed to total field anomalies as shown in fig. 10 and spectrally filtered against the wavenumber components of fig. 4. Inversely transforming all wavenumber components of fig. 10 with wavelengths greater than about 2400 km that were positively correlated with the wavenumber components of fig. 4 yields our estimates of the residual core field components in degrees 11 to 13 that are shown in fig. 11. These components can be added to the degree 11 representation of the core field to update the core field model for the Antarctic. The amplitudes of these residuals are quite small relative to the core field intensity represented by the degree 11 expansion. However, they are large compared to the intensities of the crustal Magsat components, and hence they can greatly distort anomaly interpretations.

Removing these residual core field components from fig. 10 estimates intracrustal magnetic anomalies in the Magsat data that are differentially reduced to the radial pole in fig. 12 by EPS inversion. We take these anomalies to reflect mostly intracrustal magnetization variations, but they will also reflect errors in the data and in our assumptions and analysis. Combining the intracrustal magnetic anomalies (fig. 12) with the crustal thickness magnetic anomalies (fig. 8) yields the map in fig. 13 that estimates the total crustal components in the Magsat data of the Antarctic.

3. Discussion

The crustal veracity of the Magsat anomalies in fig. 13 is problematic because the mission was flown during austral Summer and Fall periods when the capacity of the strong south polar external fields to distort crustal anomalies was maximum. Hence additional observations from other periods are required to test these Magsat components. Data from near-surface magnetic surveys are insufficient for this purpose because their long wavelength properties are seriously corrupted due to gaps in coverage and uncertainties in data leveling, secular variations, and other errors. POGO data are currently being investigated for their Antarctic crustal components (Purucker *et al.*, 1999) and will be compared with Magsat estimates. These data were obtained at all seasons and local times from 1967 until 1971, but at significantly higher orbital altitudes than Magsat. Another test of these polar crustal Magsat anomalies will result from the Ørsted/Sunsat mission (Friis-Christensen and Skøtt, 1996), which was just launched to obtain data covering all local times in circular, constant altitude orbits. This mission involves two satellites (*i.e.*, Ørsted and Sunsat) in tandem that also will aid in discriminating external field effects.

Despite these reservations concerning the level of external field contamination, the data of fig. 13 are consistent with the structure of the Antarctic crust as inferred from available gravity and topographic data, and the temporally and spatially static properties of crustal anomalies over the life time of the Magsat mission. These anomalies also are generally consistent with the large scale geological features of the region. In the offshore areas for example, prominent anomaly minima (*e.g.*, features A and B in fig. 13) overlie the marine basins off Marie Byrd Land and Wilkes Land. Analysis of the magnetic anomalies due to variations of crustal thickness (fig. 8) and intracrustal sources (fig. 12) suggests that these minima may map demagnetization effects related predominantly to crustal thinning, although hydrothermal alteration of the oceanic crust beneath the basin cover of thermally insulating sedimentary rock may also contribute (Levi and Ruddihough, 1986).

The most prominent positive anomaly (feature C) in fig. 13 overlies the Maud Rise, which is an oceanic hotspot off the Queen Maud Land coast. This maximum appears to be related to enhanced crustal thickening (fig. 8) and an intracrustal anomaly that reflects the westward extension of strongly magnetized, possibly serpentinized, oceanic crust. Additional maxima overlie the Antarctic Peninsula Microplate (feature D) and Enderby Land (feature E) that appear to be related to crustal regions of enhanced thickening. The intracrustal anomaly for Enderby Land suggests an offshore extension of highly magnetized, possibly serpentinized, rifted platform crust.

Another prominent positive Magsat anomaly (feature F) is evident for the region north of the Gamburtsev Mountains between the

Transantarctic Mountains and the western margin of the Aurora Basin. This anomaly overlies roughly the third of East Antarctica that appears to be underlain by anomalously thin crust (von Frese *et al.*, 1998). It is centered on a localized region of relatively thicker crust (fig. 8) that is surrounded by strongly magnetized (fig. 12) and thinner, possibly rifted crust.

Combining the crustal satellite anomaly estimates in fig. 13 with near-surface survey data by joint EPS inversion (Ravat *et al.*, 1998) can provide unique insight on the magnetic properties of the crust. To see how satellite magnetic measurements may be used here, consider the aeromagnetic data set for the Southern Weddell Sea Embayment and onshore regions that is shown in fig. 14 from Johnson *et al.* (1992). These data were compiled at 0.1° latitude and 0.2° longitude intervals over a 91×351 grid at an altitude of 2 km from a number of airborne magnetic surveys that were obtained over the past three decades by the Antarctic programs of the U.S., U.K. and former U.S.S.R.

As reviewed by Johnson *et al.* (1992), the aeromagnetic data in fig. 14 reveal a number of prominent anomaly-geologic associations. Along the northern boundary of the western part of the map, for example, is a portion of the prominent Pacific Margin Anomaly (PMA) that may be related to a complex mafic-intermediate batholith (Garrett, 1990). It extends some 2000 km from Thurston Island to the west through the region in fig. 14 and then northwards along the western side of the Antarctic Peninsula (Maslanyj *et al.*, 1991). Further south, prominent anomaly maxima surround the isolated Precambrian outcrop at Haag Nunataks (HN). The adjacent regions may be underlain at 5-15 km depth by Precambrian

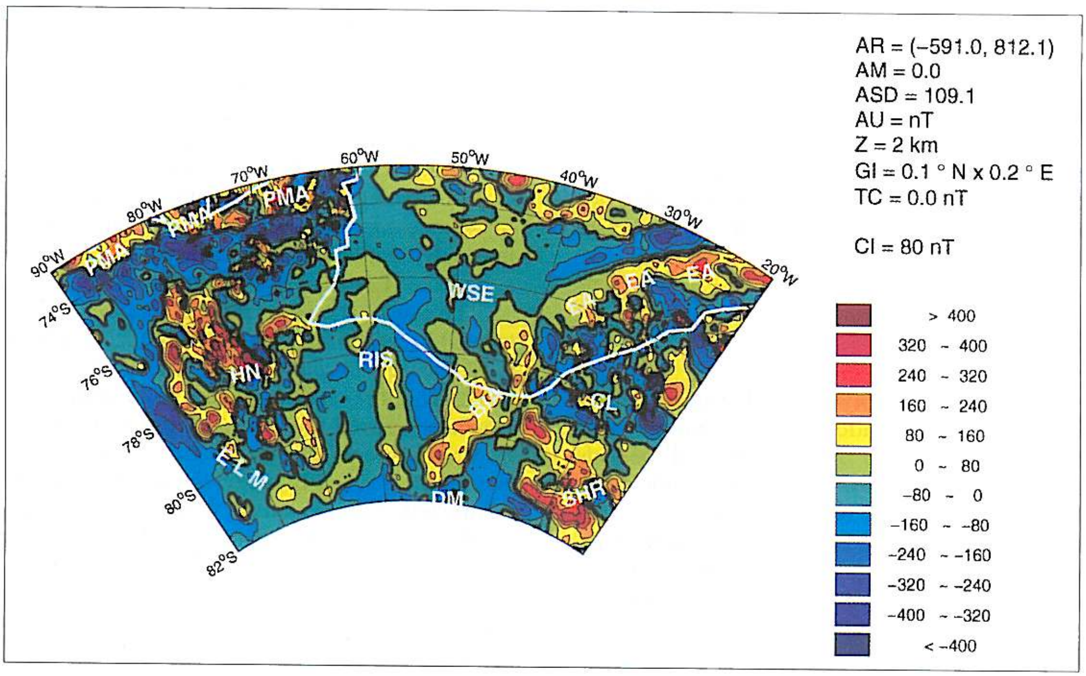

Fig. 14. Scalar total field aeromagnetic anomalies of the Weddell Province (Johnson *et al.*, 1992). Annotated features include BIA (Berkner Island Anomaly); DM (Dufek Massif); CL (Coats Land); EA (Explora Anomaly); ELM (Ellsworth Mountains); HN (Haag Nunataks); PMA (Pacific Margin Anomaly); RIS (Ronne Ice Shelf); SHR (Shackleton Range); and WSE (Weddell Sea Embayment).

basement (Garrett *et al.*, 1987; Maslanyj *et al.*, 1991) that extends possibly beneath parts of the Ellsworth Mountains (ELM) and the Ronne Ice Shelf (Maslanyj and Storey, 1990).

In the central part of the map, the Ronne Ice Shelf (RIS) and Weddell Sea Embayment (WSB) are mostly characterized by broad, low-amplitude anomalies that may reflect fairly deep magnetic basement. Beneath the Ronne Ice Shelf, more than 15 km of sediment has been inferred from the magnetic data (Maslanyj *et al.*, 1991). At Berkner Island, a major anomaly maximum (BIA) may reflect an uplifted block of Precambrian basement (Kadmina *et al.*, 1983; Maslanyj *et al.*, 1991). Further south at the Dufek Massif (DM), strong magnetic maxima overlie outcrops of layered gabbros (Behrendt *et al.*, 1981; Jankowski, 1983).

In the southeastern part of the map, prominent anomaly maxima characterize the Shackleton Range (SHR) that is underlain by Precambrian granites and gneisses (Clarkson, 1982). Further north over Coats Land (CL), well defined circular anomalies may reflect Precambrian igneous rocks that have been inferred from limited exposures (Eastin and Faure, 1971; Marsh and Thomson, 1984). Continuing further north, the large, NE-trending linear Explora Anomaly (EA) may mark a volcanic wedge of ocean-dipping reflectors (Kristoffersen and Hinz, 1991) that was produced possibly during the early breakup of Gondwana (Johnson *et al.*, 1992). Along the NE-margin of the Explora Anomaly is a prominent minimum that may reflect a postulated system of failed rift basins (Kristoffersen and Haugland, 1986; Kristoffersen and Hinz, 1991).

Noting the similarities in amplitude and wavelength, Johnson *et al.* (1992) suggested that the Berkner Island and Explora Anomalies may be linked to a deep-seated source, although no direct geological evidence was available to support either a Precambrian or Jurassic origin for these anomalies. They also suggested that the link may extend and become shallower further south to include the greater amplitude, shorter wavelength Dufek anomalies.

To more effectively relate the aeromagnetic anomalies to the satellite crustal anomalies, features in the aeromagnetic data that are not resolvable or only marginally resolvable at satellite altitude were removed. Figure 15a gives these features, which were obtained by hi-pass/low-cut filtering the data of fig. 14 for wavelengths smaller than about 400 km. The more regionally resolvable aeromagnetic anomalies with wavelengths greater than about 400 km are shown in fig. 15b. They appear to be dominated by anomaly maxima of the Haag Nunataks and Ellsworth Mountains, minima of the Weddell Sea Embayment and Ross Ice Shelf, the maximum over Berkner Island that attenuates southwards to the Dufek Massive, and the Shackleton Range maximum. The Explora and Berkner Island anomaly trend is breached by a NW extension of minima from Coats Land. A prominent maximum is also evident on the northern border at 50°W just south of where a portion of the continent-ocean boundary may be located (Johnson *et al.*, 1992).

The crustal satellite total field magnetic anomalies for the Weddell Province are given in fig. 15c for comparison. They suggest that the southern portion of the study area may be dominated by thinned magnetic crust, which would be consistent with evidence for crustal uplift that may be interpreted from the regional aeromagnetic anomalies of Berkner Island and the Dufek Massif. However, the possible relationships between the regional aeromagnetic (fig. 15b) and satellite (fig. 15c) anomalies are difficult to appreciate fully because the two data sets, by virtue of their great altitude differences, reflect vastly different sensitivities to the magnetization properties of crust.

Accordingly, to bring these relationships into better focus, the data of fig. 15b,c were jointly used to obtain an EPS model by inversion. The EPS model from the joint inversion yielded predictions that matched the data of fig. 15b,c with negligible error. Additional EPS model predictions at altitudes from 10 to 300 km are given in fig. 16a-f that illustrate the geological utility of combining near-surface and satellite magnetic observations.

For example, the predictions at 10 km (fig. 16a) strongly tend to link the Explora and Berkner Island Anomalies, whereas the anomaly extension further south to the Dufek Massif has been severly attenuated. The relatively per-

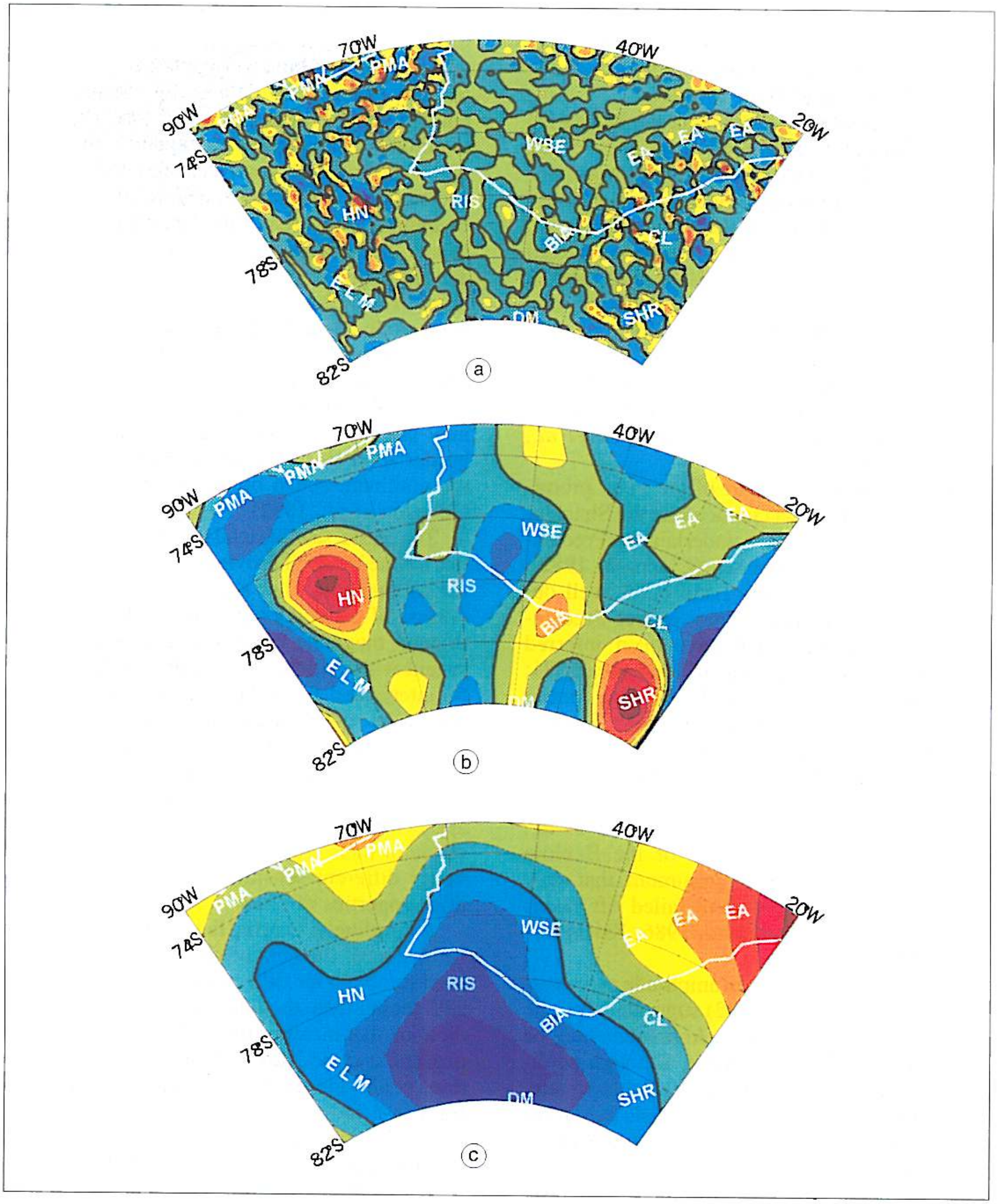

Fig. 15a-c. Magnetic anomalies of the Weddell Province include: a) aeromagnetic components of fig. 14 with wavelengths smaller than about 400 km and CI = 80 nT; b) aeromagnetic components of fig. 14 with wavelengths of about 400 km and longer and CI = 30 nT; and c) Magsat scalar total field magnetic anomalies with CI = 2 nT.

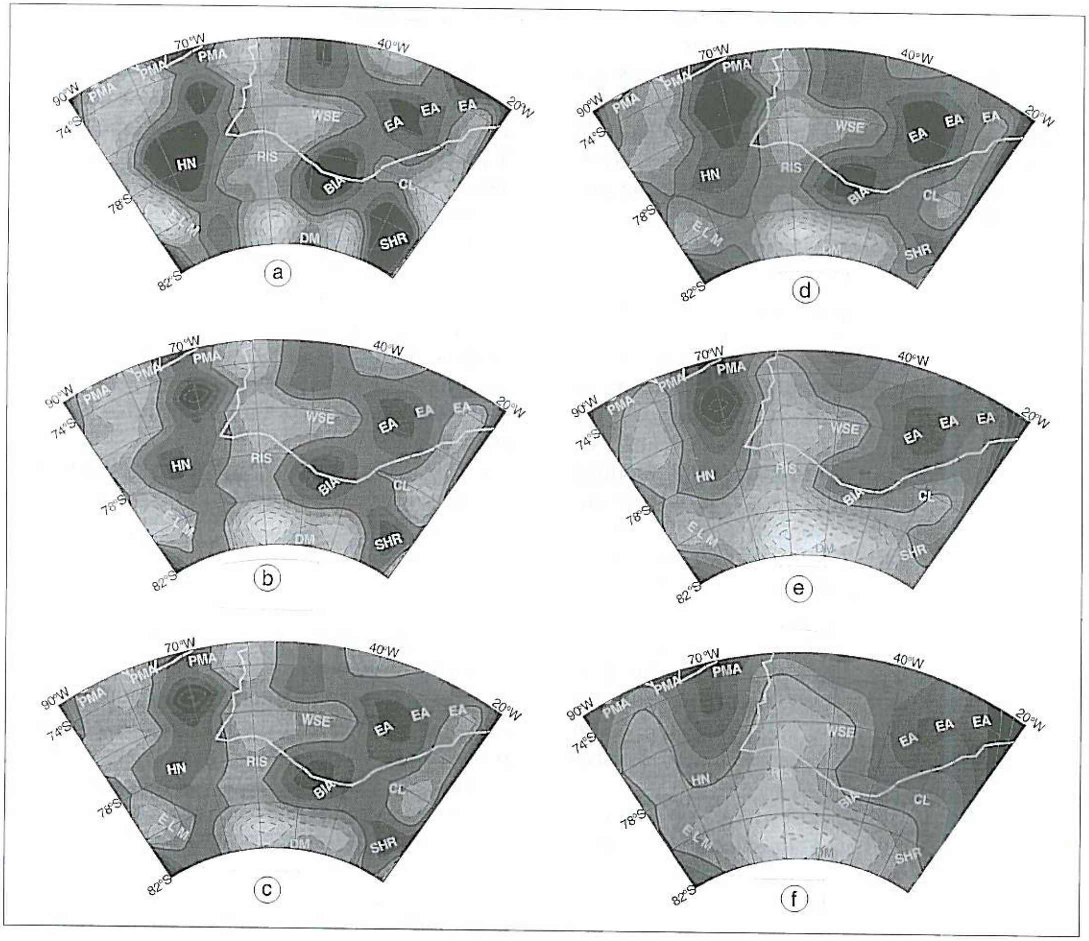

Fig. 16a-f. EPS magnetic anomaly predictions from the joint inversion of long wavelength aeromagnetic (fig. 15b) and satellite (fig. 15c) anomalies at altitudes of: a) 10 km with CI = 20 nT; b) 25 km with CI = 30 nT; c) 50 km with CI = 20 nT; d) 100 km with CI = 15 nT; e) 200 km with CI = 6 nT; f) 300 km with CI = 3 nT.

vasive nature of the crustal sources for the Explora and Berkner Anomalies is demonstrated by the well defined linkage of these anomalies up to 200-km altitude (fig. 16e). Anomaly maxima for the crustal sources of the Dufek Massif, Ellsworth Mountains, and Haag Nunataks, on the other hand, have pretty much died out at altitudes of 50 km (fig. 16c) and higher. This possible differentiation of crustal sources would have been impossible to establish from the analysis of the aeromagnetic data alone.

North of the Haag Nunataks, a prominent maximum is evident in the predictions at 10 km and higher. It may mark the southern extent of the anomalously thick magnetic crust of the Antarctic Peninsula Microplate. Satellite magnetic observations were required to reveal this feature, which in the airborne data appears to be masked by the regional minimum produced from the strong, high frequency effects of near-surface magnetization variations.

Clearly, the joint inversion of Antarctic satellite and airborne magnetic observations can provide unique qualitative and quantitative insight on the magnetic properties of the crust. These results also demonstrate the need for obtaining at intermediate altitudes supplemental magnetic data from magnetometers on high-altitude aircraft, balloons, and space shuttle tethers to better define geologic relationships between near-surface and satellite altitude magnetic fields.

If verified by the Ørsted/Sunsat mission, the crustal anomaly estimates in fig. 13 may also be downward continued to serve as a reference field for correcting regional anomaly errors in polar compilations of airborne and marine magnetic survey data. Spectral correlation analysis can be used to identify long wavelength features in the track-line data and survey grids that are inconsistent with the anomaly reference field. From these features, least-squares adjustments can be implemented to drape the track-line data and survey grids onto the anomaly reference field to yield compilations that are spectrally consistent with near-surface and satellite-altitude anomalies of the crust. Where possible for the track-line data, these adjustments also can incorporate corrections based on a least-squares cross-over analysis.

The adjustments proposed here are similar to those that we have developed for extracting marine gravity anomalies from satellite altimetry (von Frese *et al.*, 1999b). For this application, spectral correlation analysis is used between the orbital track data and a reference geoid model (*e.g.*, OSU91A, EGM96, or a more detailed model derived from a previous gravity data set) to identify long wavelength inconsistencies in the track data related to errors in orbit determination and other non-lithospheric sources. The least-squares removal of these long wavelength inconsistencies results in gravity anomaly predictions with significantly improved accuracies ($\approx$ 3 mgal or smaller errors) and resolution ($\approx$ 8-12 km near the equator, and 4-7 km near the poles) (Roman and von Frese, 1997). These procedures and experiences can be adapted to adjust near-surface and satellite magnetic data into a composite map for the Antarctic where the spectral properties of the crustal anomalies are estimated as completely as possible.

4. Conclusions

A new procedure for separating core, lithospheric and external field components in Magsat anomaly measurements has been investigated. It involves combining topographic and gravity data with spectral correlation theory to separate magnetic signals due to the core field and crustal thickness variations. Polar external fields greatly distort the properties of the core and crustal fields because they are extremely variable in space and time. Hence, until effective models of these auroral fields become available, the application of spectral correlation theory remains a principal tool for discriminating static crustal anomalies.

The Magsat crustal anomalies obtained in this investigation are generally consistent with regional geologic features of the Antarctic. Prominent magnetic minima are found overlying marine basins that appear to be related to crustal thinning and other demagnetizing effects. Magnetic maxima characterize the Antarctic Peninsula Microplate, Maud Rise, and Enderby Land as regions of mostly enhanced crustal thickness. Another positive Magsat anomaly, which may reflect a regional variation in crustal petrology, overlies roughly the third of East Antarctica between the Transantarctic Mountains and 90°E that appears to involve anomalously thin crust.

Satellite crustal anomalies were combined with aeromagnetic data by joint inversion for new insight on the possible crustal properties of Weddell Province. A regional minimum at satellite altitude dominates the south-central portion of the area that may reflect extensive thinning of magnetic crust from the Dufek Massif northwards to Berkner Island. The Explora and Berkner Island Anomalies appear to be linked by deep-seated, strongly magnetic crustal sources that may rise significantly and die out southwards to the Dufek Massif. The airborne and satellite magnetic data characterize the southern extent of the Antarctic Peninsula Microplate as a region of anomalously thick magnetic crust. In addition, for the Haag Nunataks and Ellsworth Mountains, these data invoke positively magnetized crustal regions with effects that are constrained in effect to die out at altitudes of 50 km or higher.

Procedures were also described for using satellite crustal anomalies as a reference surface for effectively merging disparate near-surface magnetic survey data. The utility of these procedures is limited only by the degree to which satellite magnetometer data may be accurately processed for crustal anomalies and downward continued to near-surface altitudes.

For the Antarctic, lithospheric applications of the Magsat data alone are problematic, however, because they are extensively contaminated by external fields that were highly agitated in the austral Summer and Fall periods when the mission was flown. The Ørsted mission will include significantly less contaminated observations taken during the austral Winter and Spring periods and hence it will provide a critical test of veracity of these procedures for estimating and using crustal anomaly components from satellite magnetometer data.

Acknowledgements

We thank Ash Johnson and the British Antarctic Survey for making available the aeromagnetic anomaly data used in this study. We also thank Tiku Ravat for an insightful review of this manuscript and his encouragement and help with implementing the joint inversion of the airborne and satellite magnetic data. Elements of this investigation were produced with support from the NASA Goddard Space Flight Center under research grant NAG 5-2996, and the Ohio Supercomputer Center at The Ohio State University.

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