MAGNETIC ANOMALIES OVER ANTARCTICA MEASURED FROM MAGSAT

M.H. Ritzwoller and C.R. Bentley, *Department of Geology and Geophysics, University of Wisconsin, Madison, Wisc., 53706, U.S.A.*

Abstract MAGSAT satellite vector magnetic anomaly data have been used to create a scalar magnetic anomaly map over Antarctica and the nearby oceans. The temporal stability of the anomaly features, together with their correlation with well-known oceanic tectonic structures, indicates that the source of the observed anomalies lies within the Earth. Specifically, magnetic anomalies are associated with oceanic basins (negative) and ridges (positive) and with such continental features as tectonic provinces (positive and negative), hypothetical rift features (negative), several mountain ranges (positive and negative), and a subglacial basin(positive). At least two of the largest magnetic anomalies in Antarctica are mirrored by anomalies at the corresponding locations in other Gondwana continents. The map appears to possess information relevant to the large-scale structure and development of Antarctica, but must be used with care due to ambiguities inherent in its interpretation.

It is fortunate and surprising that magnetic fields generated by crustal sources can be isolated in satellite magnetic field data from those generated in the core and those external to the earth. It is surprising because crustal fields (<25 nT) are so much smaller than the core field (30,000-70,000 nT) and external fields (0-2,000 nT), and fortunate because geologic and tectonic features in the deep crust can result in long wave-length magnetic anomalies (Pakiser and Zeitz, 1965; Zeitz et al., 1966; Hall, 1974; Krutikhovskaya and Pashkevich, 1977). Long wave-length magnetic anomalies were first mapped globally from data acquired by the POGO (Polar Orbiting Geophysical Observatories) satellites (Regan et al., 1975) and have been shown to correlate well with upward-continued regional aeromagnetic surveys (Langel et al., 1980). The chief advantage of the MAGSAT data over the POGO data lies in the ability to study vector fields with MAGSAT and in the greater resolution MAGSAT's generally lower orbit (350-560 km compared to 400-1500 km for POGO) affords. For a further description of MAGSAT see Langel, Ousley et al., (1982).

Attempts have been made to isolate anomalies both in the scalar field (Langel, Phillips and Horner, 1982; Coles et al., 1982; Ritzwoller and Bentley, 1982) and in the vector field (Langel, Schnetzler et al., 1982; Coles et al., 1982). Sailor et al., (1982) confirm the general reliability of such attempts and conclude that resolution is possible down to a 250 km spatial wave length in mid-latitudes. Resolution is poorer in higher latitude regions due to the smaller signal to noise ratio that is the consequence of larger external magnetic fields in the auroral regions. Magnetospheric ring-currents in low latitudes generate a long spatial wave-length signature that varies relatively slowly and is easily filtered. However, currents following magnetic field lines in auroral regions have spectra covering a broad band of both temporal and spatial frequencies, thus making filtering difficult. Therefore, only data from passes occurring while field-aligned currents are small can be used in high latitudes, seriously reducing the size of the data set over Antarctica and in the Arctic (Coles et al., 1982). The pronounced radial striping displayed by the anomalies in the Antarctic map of Ritzwoller and Bentley (1982) demonstrates the signal detection problem. In this paper we will present an improved data reduction scheme and a scalar magnetic anomaly map that we believe better approaches the true crustal magnetic field.

The modelling and interpretation of satellite magnetic anomaly maps has a short history and progress is mostly qualitative. On a global scale, anomalies appear to be associated with such large structures as continental shields and platforms, subduction zones (positive), oceanic ridges (positive), and abyssal plains (negative) and appear to be bounded by such "linear" features as sutures, rifts, folded mountains, and age province boundaries (Frey, 1982a). Preliminary regional studies have been performed by Frey (1982b) for Asia, by Hastings (1982) for Africa, by Hinze et al., (1982) for South America, and by Ritzwoller and Bentley (1982) for Antarctica.

Geologic interpretation of the anomalies can only be conducted in the light of the probable mineralogy of the lower crust and upper mantle. Wasilewski et al., (1979) argue that the mantle is probably non-magnetic, so if the Curie isotherm is below the crust the lower-magnetic boundary is the Moho. Moreover, Wasilewski and Mayhew (1982) conclude that, at least for some tectonic settings, the lower crust is the most magnetic crustal layer, and that magnetisation values for lower crustal xenoliths (specifically metabasic rocks of the granulite facies) have values consistent with those inferred from models of long wave-length anomalies. Wasilewski and Fountain (1982) corroborate these findings with a study of the Ivrea Zone in northern Italy, where mafic granulite facies rocks are the only magnetic lithology present and are thick and laterally continuous, thus providing a good candidate for a deep-crustal source of long wave-length magnetic anomalies.

Along with regional mineralisation variations, it is likely that variations in the depth to the Curie isotherm (if above the Moho) will be reflected in the long wave-length anomalies (Mayhew, 1982). Thus, the main sources of long wave-length magnetic anomalies in continental regions are expected to reside above the Moho and the Curie isotherm but principally in the lower crustal layer. It follows that, *ceteris paribus*, regional magnetic anomalies depend inversely on heat flow, and directly on the thickness of the magnetised crust. Therefore, continental highs indicate some combination of a thick lower crust, low heat flow, and higher than normal average magnetic susceptibility in the lower crust, whereas continental lows imply a thin crust, high heat flow, and/or low susceptibilities in the lower crust. It remains uncertain to what degree continental remanent magnetisation may affect long wave-length magnetic anomalies. Galliher and Mayhew (1982) argue that the effect is small.

The base of the oceanic crust, of course, lies much nearer to the surface than that of the continental crust—generally far above the Curie isotherm, except right at the spreading centres. Thus, oceanic magnetic anomalies should reflect regional crustal thicknesses and susceptibility differences, but generally not heat flow. Oceanic basins should be magnetically negative relative to continental regions. Over oceanic spreading centres, however, as has been shown by model calculations, the broad axial region of positive remanent magnetisation results in a positive anomaly, even at satellite elevations.

Data Reduction

Ritzwoller and Bentley (1982) described a method by which a preliminary map of the crustal scalar magnetic field was produced. The method was designed to filter non-crustal magnetic fields using scalar magnetic field data alone. However, a great deal of information concerning the influence of field-aligned currents is available in the vector magnetic field data; we have now used that information as part of our data selection procedure, which we will now outline.

Only satellite passes over Antarctica that took place during a magnetically quiet time period (planetary magnetic activity index, Kp, no greater than 1^- for 6 hours) were considered. Of the approximately 2400 passes over Antarctica between 1st November 1979, and 1st April 1980, 212 met this selection criteria. For these, scalar field values were calculated from the observed vector data, and differences were taken relative to spherical harmonic core field model MGST (4/81), of degree and order 13, created by Langel, et al., (1980). Next a second degree polynomial least squares fit was subtracted from each pass to filter the effects of magnetospheric ring-currents, errors in the core field model, and other errors in measurement (for more details see Langel, Phillips and Horner, 1982). Since the vector data indicate that more than half of the passes remain seriously affected by field aligned currents, passes were accepted for final use only if they satisfied the following three criteria:

(a) the maximum amplitude of the vertical vector anomaly, ΔZ, is less than 25 nT;
(b) the maximum amplitude of the scalar anomaly, ΔB, is less than 20 nT;
(c) ΔZ and ΔB are highly correlated.

(For a more detailed discussion of our use of the vector components in data selection, see Ritzwoller, 1982)

The 88 passes selected in this manner appear to provide a reasonable balance between providing a sufficient density of data (Figure 1.) and reducing field-aligned current effects to an acceptable level. Scalar field values calculated from these passes were averaged in

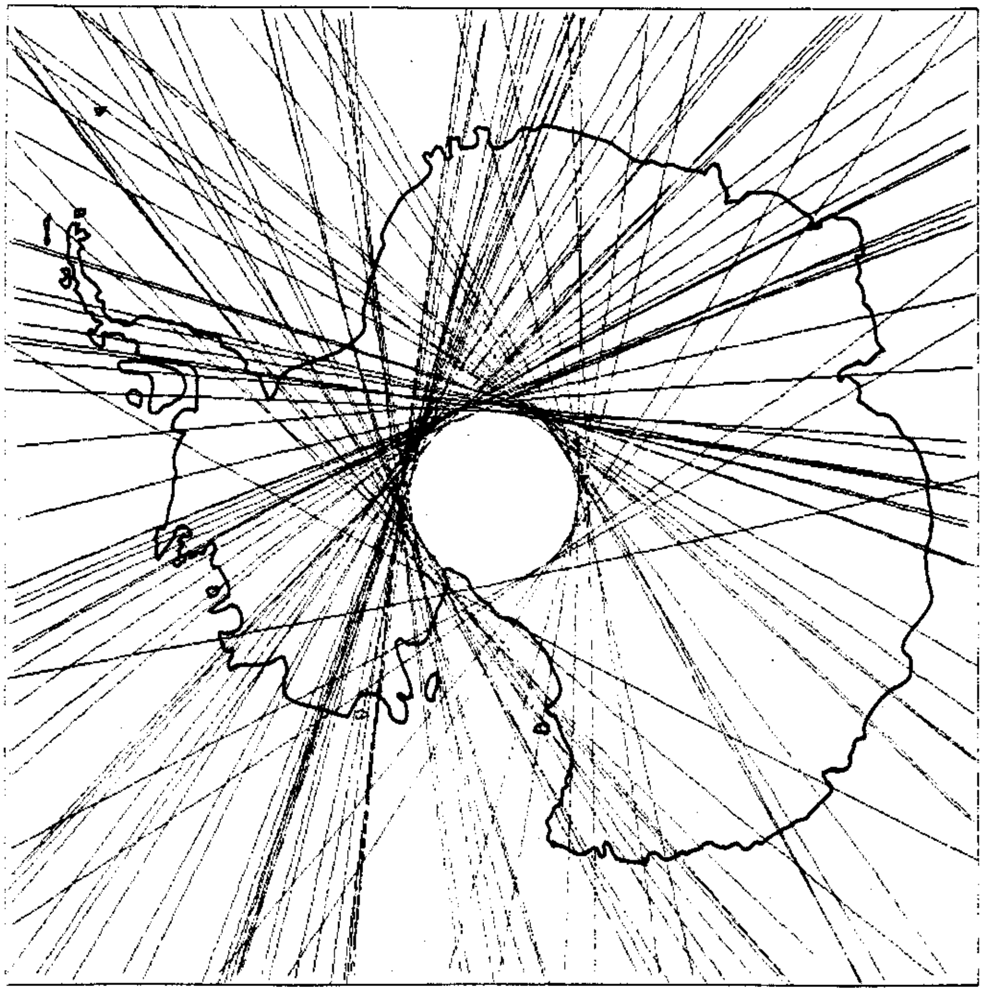

Figure 1. Flight tracks of the 88 passes used to construct the magnetic anomaly map in Figure 2.

square bins measuring 330 km on a side, and standard deviations were calculated. Following a check to make sure that the values within the bins were normally distributed, outliers were rejected and the average and standard deviation were recomputed. The averages were then plotted and hand-contoured, yielding the final anomaly (Figure 2.). The average standard deviation is 1.5 nT, leading to an estimate of the standard error in the means of only a few tenths of a nannotesla.

The anomalies on this map have not been reduced to the pole; since all of Antarctica (except the Antarctic Peninsula) is above 60° in geomagnetic latitude, reduction to the pole would have only a small effect. Nor have data been continued to a single elevation before averaging—studies performed elsewhere (R. Sailor, personal communication, 1982) indicate that maps created by simple averaging are "qualitatively and quantatively similar" to those for which passes are first continued to the average elevation (470 km from our data set).

The scalar anomaly map in Figure 1 is a significant improvement over the preliminary map presented in Ritzwoller and Bentley (1982)—we believe it to be a good approximation to the true crustal anomaly field. The data appear internally consistent within the five months of data acquisition (Ritzwoller, 1982), and the map correlates well with the POGO map for Antarctica. Thus, the features are temporally stable, a necessary characteristic of fields produced in the crust.

Geological Interpretation

The interpretation of MAGSAT data, though still in its infancy, should hold great interest to the Antarctic geoscientist, for here is the first coherent continent-wide data set with information about the Antarctic crust. Furthermore, MAGSAT magnetic anomalies appear to be highly correlated with known Antarctic geologic and tectonic features, especially in oceanic regions where the geology is simplest and best known.

Oceanic magnetic anomalies are almost invariably associated both with basins (negative) and spreading ridges (positive). (All oceanic feature names will be taken from Heezen and Tharp, 1980). Three of the four major oceanic basins surrounding Antarctica (the Weddell, Enderby and Wilkes Abyssal Plains, the exception being the Bellingshausen Abyssal Plain) have negative anomalies associated with them. (Geographic names are indexed in Figure 2.) The most striking conjunction of a positive anomaly with a spreading ridge occurs where the Mid-Indian Ocean Ridge and the East Pacific Ridge meet grid south of the Ross Sea embayment ("grid" directions refer to a Cartesian co-ordinate system laid across the polar map, with grid north parallel to the 0° meridian, grid east parallel to 90°E, etc.). The set of positive anomalies running between 140°E and 120°W, north of 65°S, lies closely over the East Pacific Ridge on the grid west and the Mid-Indian Ocean Ridge on the grid east. There are also highs associated with aseismic volcanic ridges and plateaus, such as the Kerguelen Plateau (about 80°E) and Maud Rise (65°S,0°E), and a relative high in an otherwise pronounced low is associated with the South Sandwich Islands and Trench (60°S, 25°W).

There are, however, some interesting anomalies that do not fit this norm. For example, a positive anomaly runs grid northeast from Maud Rise right into the Enderby Abyssal Plain, and another extends grid west of Thurston Island into the Bellingshausen Abyssal Plain. The cause of these anomalies is puzzling, and deserves further study.

The correlation between magnetic anomalies and continental structures is also striking. In East Antarctica, the mountains of Queen Maud Land (negative), the mountains of Enderby Land (positive), much of Wilkes Land (positive), the Gamburtsev Subglacial Mountains (negative), and the Amery Ice Shelf (negative) all have magnetic anomalies associated with them. Although it is not certain, of course, what these anomalies mean, some speculation may nevertheless be useful. We believe that the Enderby Land high may stem from a relatively high crustal magnetisation—aeromagnetic surveys in parts of the area (Wellman and Tingey, 1982) suggest to us the mean susceptibility of the upper crustal rocks, at least, is higher than the continental norm. We suggest that the low over the Gamburtsev Subglacial Mountains results from an elevated Curie isotherm; this idea finds some support in the low surface-wave group velocities along paths traversing these mountains (Dewart and Toksöz, 1965; see discussion in Bentley, this volume), since a warming of the mantle causes seismic wave velocities to diminish. Perhaps these mountains are relatively young. The pronounced relative magnetic low overlying the Amery Ice Shelf/Lambert Glacier region supports the belief that this is a failed rift (Masolov, et al., 1981); most continental rift features show a negative anomaly (Frey, 1982a). The apparent extension of the anomaly into the ocean is probably just a failure to resolve closely adjacent continental and oceanic lows.

On a larger scale, the coincidence of depressed topography, satellite-measured free-air gravity lows, and other features extending from Wilkes Land across the ocean into Australia, led Veevers (1982) to

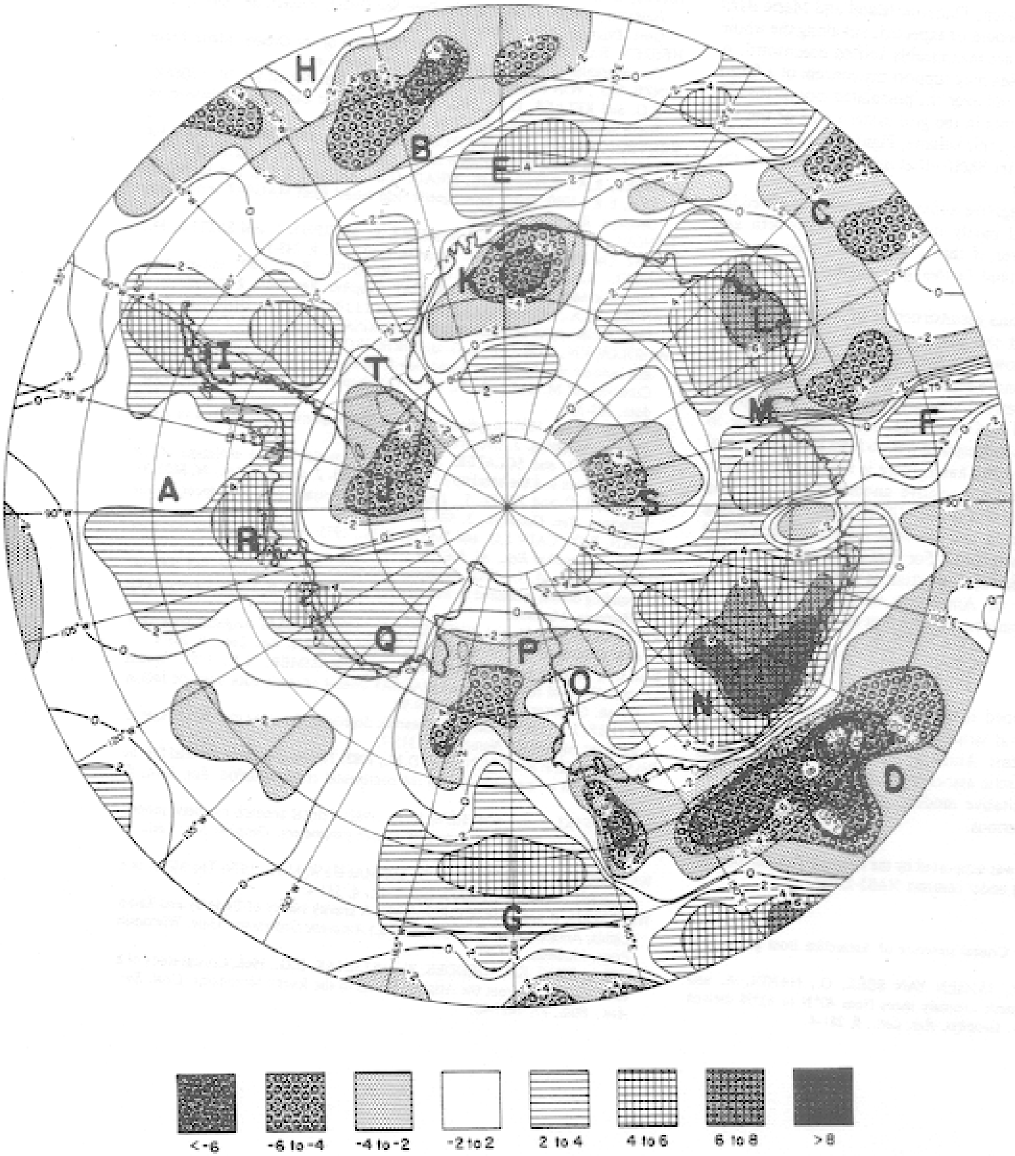

Figure 2. MAGSAT total field magnetic anomaly map over Antarctica. Units in nT. Average elevation 470 km. Capital letters indicate the approximate location of: A—Bellingshausen Abyssal Plain; B—Weddell Abyssal Plain; C—Enderby Abyssal Plain; D—Wilkes Abyssal Plain; E—Maud Rise; F—Kerguelen Plateau; G—juncture of the Mid-Indian Ocean Ridge and the East Pacific Ridge; H—South Sandwich Islands; I—Antarctic Peninsula; J—Ellsworth Mountains; K—Queen Maud Land; L—Enderby Land; M—Amery Ice Shelf/Lambert Glacier; N—Wilkes Land; O—Transantarctic Mountains; P—Ross Sea embayment; Q—Marie Byrd Land; R—Thurston Island; S—Gamburtsev Mountains; T—Weddell Sea embayment.

suggest that the whole vast region is being held down dynamically by downward currents in the mantle. The positive magnetic anomaly in Wilkes Land (and the corresponding one in Australia—see below) is consistent with this suggestion since the convection-convergence zone would be relatively cool.

A noteworthy feature of the anomaly map is the absence of magnetic anomalies over the Transantarctic Mountains. Instead of exhibiting a characteristic anomaly pattern of their own, they mark a distinct boundary zone between largely separate East and West Antarctic anomalies. (It is likely that the negative anomaly that cross-cuts them from the Ross Ice Shelf is, in fact, another case of two separate lows that have not quite been resolved.)

Several anomalies appear in West Antarctica, but their tectonic association is not at all clear. The volcanic province or provinces comprising the Antarctic Peninsula, Thurston Island and Marie Byrd Land all show distinct highs as would be expected, but along the whole region the centres of the highs are inexplicably shifted oceanward. A pronounced low over the Ross Sea may support the concept of a failed rift zone here, but it is not centred over the postulated axis of the rift found from gravity measurements in the grid eastern part of the sea (Hayes and Davey, 1975; Bentley, this volume, Figure 9.).The anomaly does disappear under the Ross Ice Shelf—that is in agreement with the gravity evidence (Davey, 1981).

What may be a mirroring negative anomaly appears in the Weddell Sea embayment between (and partly overlying) the Ellsworth and Pensacola Mountains. However, if this is a rift-zone negative, it is surprising that is does not extend farther grid northward under the Weddell Sea continental shelf.

Comparison of the Gondwana reconstruction of Norton and Sclater (1979) with Figure 2 and the global anomaly map of Langel, Phillips and Horner (1982) shows that the pronounced high in Wilkes Land is mirrored by an even more pronounced high in the Australian shield; there is, in fact, a general similarity between the magnetic appearances of Wikes Land and Australia. Moreover, the low in Queen Maud Land appears to correspond well to lows in southern and southeastern Africa. On the other hand, there is no clear correspondence between the West Antarctic positive anomalies and anything else. It appears, unfortunately, that the MAGSAT map is not yet going to solve the puzzle of where to put the West Antarctic microplates before the breakup of Gondwanaland! For East Antarctica, nevertheless, the Gondwana magnetic reconstruction is very good, implying that the anomaly features in Antarctica were formed prior to breakup. A more exact comparison requires that all data be reduced to the pole.

Conclusions

Magnetic anomalies mapped in Antarctica from MAGSAT data reflect real features of crustal structures, and many of them can be understood qualitatively. East Antarctic Gondwanian associations appear clear, but West Antarctic associations do not. Further analysis should lead to more quantitative models, and to interpretations of features that are now mysterious.

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