Exploration Geophysics (1995) ***26****, 215-220*

Magnetic mineralogy of the Black Hill Norite and its aeromagnetic and palaeomagnetic implications

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ABSTRACT

The Black Hill Norite is a mafic intrusion which formed around 487 Ma ago. It intruded sediments of the Kanmantoo Group and Adelaide Supergroup which were deformed and metamorphosed during the Delamerian Orogeny. The unusual aeromagnetic anomaly caused by the norite gave the first indication of the presence of natural remanent magnetisation (NRM) totally different from the present field direction.

The Black Hill Norite exhibits a strong remanent magnetisation (declination = 221.2 degrees, inclination =7.6 degrees, and intensity =4.9 A/m) indicating that it was intruded at equatorial latitudes. The remanence is probably thermal in origin. The known amount of coarse-grained multi-domain magnetite present is sufficient to explain the high magnetic susceptibility. The stable and intense remanence is carried by fine-grained single-domain pure magnetite.

Demagnetisation and hysteresis studies suggests the presence of two populations of single-domain magnetite with nearly parallel but consistently different remanent directions. Preliminary electron probe work has confirmed the presence of randomly oriented fine-grained magnetite in the rock matrix as well as magnetite exsolved out of pyroxenes and feldspars. The bimodal NRM direction can be explained as due to secular variation associated with slightly different times of NRM acquisition or due to a shape anisotropy (caused by the orientations of the exsolved single-domain grains being confined to particular crystallographic directions within the host silicates, which in turn, show a preferential orientation, possibly indicating magma flow directions).

The 3D analytic signal map and the reduced to the pole map, both made from calculations on the total magnetic intensity data, are similar, thus demonstrating the dual application of the analytic signal in the interpretation of low latitude surveys and the interpretation of magnetic sources suspected of carrying a strong, but unknown, remanent component.

The Black Hill Norite is an excellent palaeomagnetic recorder. It provides evidence for the Early Ordovician palaeomagnetic pole position for Australia (interpreted as being near the African Bight in a standard Gondwana reconstruction) which was previously in doubt because of the absence of reliable data. The success of this study illustrates how aeromagnetic maps, by indicating the presence of remanently magnetised rock units, can be constructively used to select sampling sites for NRM studies.

Keywords: Delamerian Orogeny, Black Hill Norite, natural remanent magnetisation (NRM), hysteresis loop, alternating field (AF) and thermal demagnetisation, coercive force, saturation remanence, saturation magnetisation

INTRODUCTION

The Black Hill Norite, found 83 km ENE of Adelaide (see Figure 1), is believed to have formed during the Ordovician period. It gives rise to a 3000 nT aeromagnetic anomaly which has a strong negative peak in the northeast and a similar positive peak in the southwest (Figure 3). Since the anomaly could not be explained by the local magnetic inclination and declination (-65 degrees and 8 degrees respectively), it was obvious that the rock must carry a strong component of natural remanent magnetisation (NRM) quite different from that of the present field (Rajagopalan et al., 1993). NRM measurements (Schmidt et al., 1993) revealed a high magnetic susceptibility (2000 to 5000 X 10^{-5} SI units) and a very stable remanent magnetisation with the following properties: declination = 221.2°, inclination =7.6° (α_{95}=4°), intensity =4.9 A/m giving a Koenigsberger ratio of approximately 2.

The main magnetic minerals, the titanomagnetites and titanohaematites, are typically present as accessory minerals in most rocks and yet, they can be the source of detectable aeromagnetic anomalies. Sometimes optical microscopy, electron microscopy and analytical methods can be applied successfully to determine the composition, size and shape of the magnetic grains (Morgan and Smith, 1981). However, in many cases, it is much easier to use the magnetic properties of the minerals to identify and characterise them (O'Reilly, 1984). From thermomagnetic studies, results of AF demagnetisation, and measurements of hysteresis loops, additional information on the magnetic mineralogy of the Black Hill Norite has been obtained and is presented here. Some of these results have been checked against preliminary optical and electron microscopy investigations.

The 3D analytic signal (defined to be the square root of the sum of the squares of the vertical and two horizontal derivatives of the total magnetic intensity) is often useful in

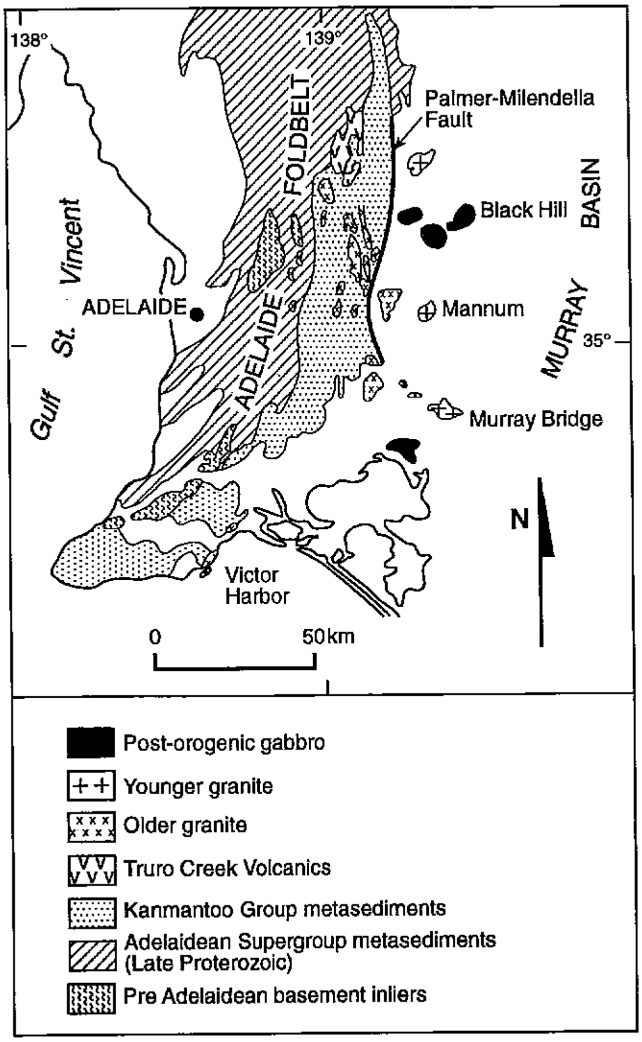

Fig. 1. Simplified geological map of part of the Adelaide Foldbelt.

delineating the boundaries of magnetic sources, especially when other techniques fail because the magnetic source is at or near the magnetic equator or is remanently magnetised. From the interpretation point of view, the Black Hill magnetic anomaly provides an excellent test case by which to compare the 3D analytic signal and reduction to the pole.

GEOLOGY

Sediments of the Adelaide Supergroup and overlying Kanmantoo Group (see Figure 1) were deformed and metamorphosed during the Delamerian Orogeny, about 505 Ma. Igneous rocks found in the southern Adelaide Foldbelt can usually be classified with respect to the onset of the orogeny as being either pre-, syn- or post-tectonic. Post-tectonic intrusives include intrusives formed during the closing stages of the deformation. Typically the pre-tectonic and syn-tectonic igneous rocks tend to be granitic and are found within the foldbelt west of the Palmer-Milendella fault zone. The known post-tectonic intrusives are bimodal (though again granitic rocks predominate) and form part of the western margin of the basement to the present Murray Basin.

Exposures of the basement east of the fault zone are restricted to the extremely limited outcrop of a few granitoid tors and the Black Hill Norite. Most basement features have been identified mainly on the basis of regional aeromagnetic maps in combination with gravity data, borehole control, sparse seismic profiles and the known outcrops. Specific magnetic anomalies have been correlated with exposed A-type granites, gabbros, metasediments (possible Kanmantoo Group or Adelaide Supergroup equivalents) and possible volcanics (Brown et al., 1988; Rajagopalan, 1989; Bontenakel, 1992).

The exposed intrusives are undeformed and their intrusion is believed to have marked the cessation of the Delamerian Orogeny. The granites and gabbros may have originated through extended fractionation of basaltic magmas. They appear to be compositionally and spatially distinct from the deformed granites (pre- and syn-tectonic) found in the Adelaide Foldbelt (Sandiford et al., 1992; Turner et al., 1992a and 1992b). The bimodal post-tectonic igneous suite suggests a period of extensional tectonics which commenced shortly after the close of the Delamerian Orogeny.

The Black Hill Norite (Wegmann, 1980) is a major but poorly exposed mafic intrusion to the east of the Mt. Lofty Ranges north of Mannum in South Australia. The Black Hill complex comprises several large, layered plutons with a continental tholeiitic nature. The range of lithologies extends from peridotites and troctolites through olivine gabbros and norites to gabbronorites and pyroxene monzonites as well as late dyke-like equivalents of the post-tectonic granites. It is not metamorphosed and observed deformation is restricted to discrete shear zones and is therefore regarded by Turner (1991) as effectively post-tectonic.

Milnes et al. (1977) report a Rb-Sr biotite-whole rock isochron from the Black Hill gabbros which gave an age of 487 ± 5Ma and they also gave a K-Ar date on the biotite of 486 Ma indicating that there appears to have been no significant thermal perturbation subsequent to crystallisation. A seven point Nd-Sm mineral-whole rock isochron (Turner, 1991) yielded an age of 489 ± 10Ma.

ROCK MAGNETISM

Schmidt et al. (1993) and Rajagopalan et al. (1993) analysed oriented samples of the Black Hill Norite. Their studies revealed that the Black Hill Norite displays a very stable remanent magnetisation with the following properties: declination = 221.2°, inclination =7.6° (α_{95} = 4°), intensity =4.9 A/m and a Koenigsberger ratio of approximately 2. Outcrop susceptibility measurements ranged from 2000 to 5000 X 10^{-5}SI units.

They detected the presence of only one component of NRM, albeit with a slightly bimodal distribution of directions. Demagnetisation to various degrees resulted in a lowering of the NRM intensity but the direction remained relatively constant. From the very high palaeomagnetic stability, Schmidt et al. (1993) concluded that the Black Hill Norite contains single- or pseudo-single domain grains of magnetite as well as the abundant multi-domain magnetite which is visible through a reflecting-light microscope. The high susceptibility arises mainly from 1 to 2 % of multi-domain (MD) magnetite, while the stable and intense NRM is carried by the single-domain (SD) or pseudo-single domain (PSD) magnetite. The NRM is probably thermoremanent magnetisation acquired during the cooling of the Black Hill Norite, as it has not been significantly heated or deformed since it was formed.

In this study, the magnetic mineralogy of the Black Hill Norite was characterised using hysteresis loops, alternating field (AF) coercivity spectra, unblocking temperature spectra and low-field thermomagnetic (k-T) curves. Figures 2a and 2b show typical hysteresis (J-H) loops obtained with a modified Arun Electronics hysteresis loop tracer that has been interfaced to a PC. Most samples (e.g. BHN02D) exhibit thin loops which reflect predominantly multi-domain character, with low coercive force ($Hc < 50$ Oe) and relative remanence $Jrs/Js < 0.05$, as in Figure 2a. Some samples, however, show mixed SD/MD characteristics, indicating the presence of ultrafine grains, less than a few microns long, as well as grains larger than 10 microns. Figure 2b shows a J-H loop for sample BHN04E, for which $Hc = 94$Oe and $Jrs/Js = 0.1$. The highest coercive force and relative remanence measured were 150 Oe and 0.16 respectively in sample BHN03D, which indicates that a substantial proportion of SD grains are present in that sample. Hysteresis loops were also measured at low temperatures (-196°C), as large increases in coercive force and relative remanence at low temperature are diagnostic of Ti-rich titanomagnetite (> 40 mole % ulvospinel). However no increases in these properties were observed, showing that highly titaniferous magnetite is absent.

Low-field thermomagnetic curves for samples BHN02D and BHN04E are shown in Figure 2c and Figure 2d respectively. The k-T curve for BHN02D is fairly reversible, indicating little chemical change has occurred during or after heating to 650°C. The low temperature susceptibility peak around -155°C (the isotropic point of magnetite) is diagnostic of the presence of nearly stoichiometric magnetite in the MD size range. However this peak is less prominent and is broader than that associated with pure magnetite, suggesting that there is a small range of compositions, from pure magnetite to slightly titaniferous magnetite. The rounded knee of the curve at approximately 500°C and its slope between 500°C and 600°C indicate a distribution of Curie temperatures within this range, corresponding to ulvospinel contents of 0 to 10 mole %. The k-T curve for sample BHN04E exhibits a peak at -180°C, followed by a drop in susceptibility up to room temperature, and an irreversible hump at intermediate temperatures. Reversibility checks show that this latter feature is not a magnetic transition, but represents a chemical change, which is attributed to the breakdown of (titano)maghaemite at around 400°C. The high temperature portion of the curve is similar to that of sample BHN02D. Taken together the k-T curves suggest that the SD grains in BHN04E are predominantly titanomaghaemite, which is unstable on heating above 400°C, whereas the MD grains are magnetite and slightly titaniferous magnetite. The hysteresis properties show that for most samples MD grains are volumetrically dominant. This implies that the susceptibility is predominantly due to MD grains. However, SD grains are much more efficient carriers of remanence than MD grains, because SD particles have much higher Koenigsberger ratios and exhibit higher palaeomagnetic stability. Thus, if present in significant amounts, SD grains can dominate the remanence of rocks, even though the susceptibility is mainly produced by MD grains. Figure 2e shows typical behaviour for AF demagnetisation of NRM. The NRM of the Black Hill Norite is very resistant to AF demagnetisation and is not completely demagnetised below 2500 Oe in some cases. The coercivity spectra derived from the AF demagnetisation curve show bimodal distributions, with peaks below 100 Oe, corresponding to MD grains, and broad peaks from approximately 600 to 1500 Oe, representing small PSD and SD grains with sizes from a few microns to submicron. The highest coercivities correspond to submicron grains with highly acicular shape.

Thermal demagnetisation characteristics of NRM are illustrated by Figure 2f. The small change in the NRM vector after cooling to -196°C and rewarming in zero field indicates demagnetisation of the relatively small component of remanence carried by MD magnetite. The demagnetisation curve is then almost flat up to 500°C, whereupon it descends steeply down to the Curie point of magnetite at 580°C. This "square-shouldered" curve indicates that the remanence carriers have ideal palaeomagnetic characteristics. Primary remanence carried by such grains cannot be overprinted below about 500°C. No detectable demagnetisation occurs in the range 350°C to 450°C in any sample, indicating that maghaemite is not carrying significant remanence. This suggests that any maghaemite that may be present in the samples is a product of recent weathering, rather than a primary phase.

Overall, the rock magnetic experiments show that the Black Hill Norite contains magnetite and low-Ti titanomagnetite grains with a bimodal size distribution. The susceptibility is mainly attributable to relatively large MD grains (typically tens to hundreds of microns), with a lesser contribution from SD grains, whereas the remanence is dominated by ultrafine SD grains. The presence of substantial amounts of high coercivity, high unblocking temperature SD grains accounts for the palaeomagnetic stability, the intense remanence and the high Koenigsberger ratio.

OPAQUE MINERALOGY

Preliminary optical and electron microscopy studies indicate the presence of magnetite, ilmenite and haematite. Of these phases, only magnetite is strongly magnetic. The coarse-grained magnetites range from approximately 200 microns to 400 microns in size and are either subhedral or euhedral. Additionally, lath-shaped exsolution lamellae (dimensions of the order of 3 microns by 40 microns) within pyroxenes and feldspars were tentatively identified as being magnetite and need to be checked by using the electron probe.

Turner (1991) identified pyrite, hemo-ilmenite and magnetite (sometimes with exsolved hercynite) in the Black Hill Complex. The magnetite and ilmenite are found as separate phases.The ilmenites are Ti-rich while the magnetites contain very little titanium. The total amount of opaques present can exceed 5% though the typical value is nearer 2%. Magnetite is sometimes found exsolved out of biotite and clinopyroxene. The known amount of relatively coarse-grained (and therefore multi-domain) magnetite present is sufficient to explain

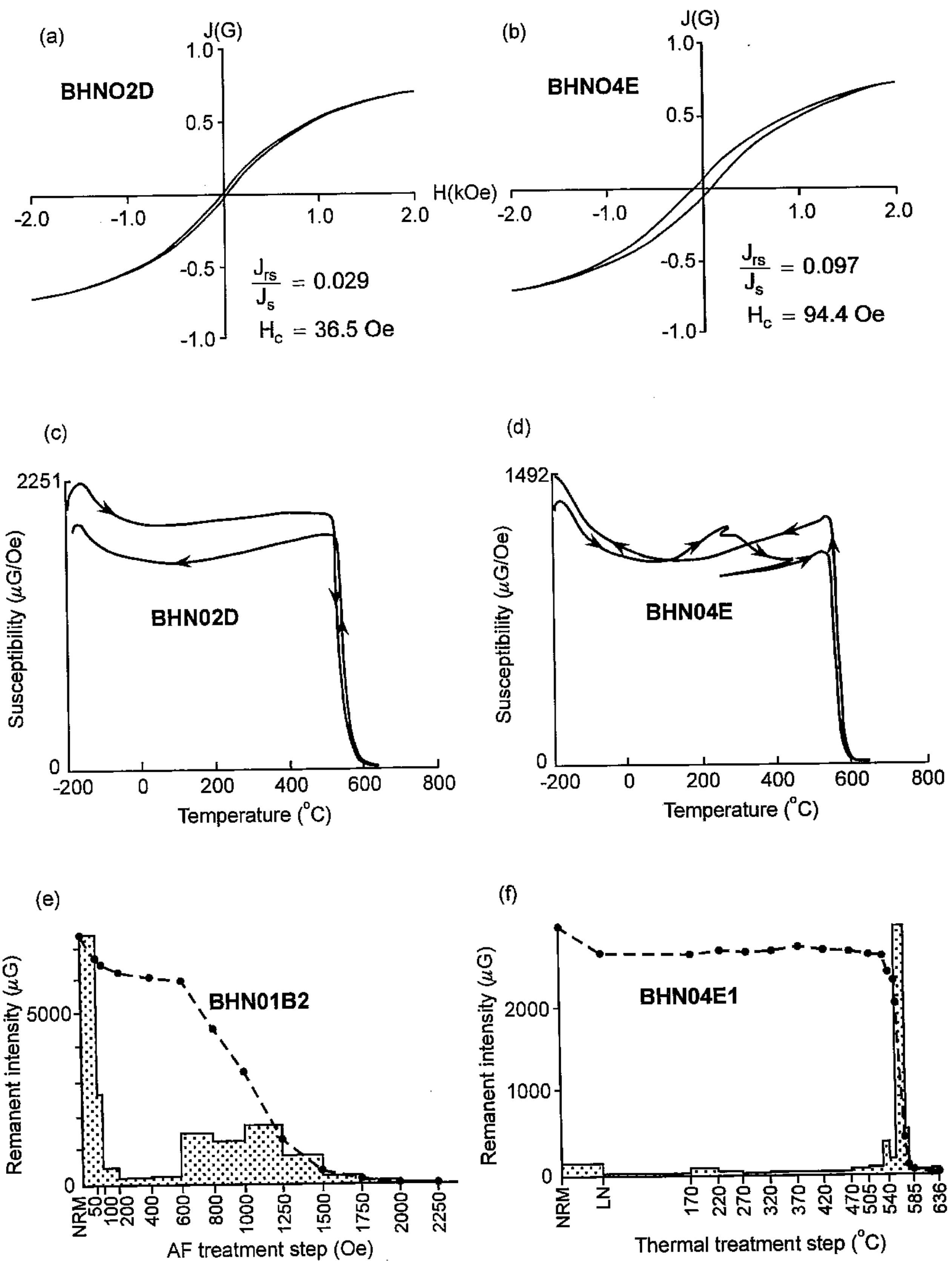

Fig. 2. Results of rock magnetism experiments. (a) Near-saturation hysteresis (J-H) loop for BHN02D, showing predominantly MD characteristics. *Hc* = coercive force, *Jrs/Js* is the relative remanence (saturation remanence/ saturation magnetisation). Vertical axis represents magnetisation in μG, horizontal axis represents applied field in oersteds. The maximum field is 2000 Oe. (b) J-H loop for BHN04E, showing mixed SD/MD behaviour. (c) Low-field thermomagnetic (k-T) curve for BHN02D. Vertical axis represents approximate susceptibility in μG/Oe (=10^{-6} CGS). (d) Low-field thermomagnetic (k-T) curve for BHN04E. (e) AF demagnetisation curve and corresponding AF coercivity spectrum for specimen BHN01B2. (f) Thermal demagnetisation curve and corresponding unblocking temperature spectrum for specimen BHN04E1. LN represents cooling in liquid nitrogen and rewarming in zero field.

the high magnetic susceptibility but is unlikely to be the cause of the stable and intense remanence. The acicular single-domain grains inferred from rock magnetism experiments are probably ultrafine magnetite particles exsolved within pyroxenes and plagioclase.

A COMPARISON OF THE 3D ANALYTIC SIGNAL AND REDUCTION TO THE POLE

The Bureau of Mineral Resources (now the Australian Geological Survey Organisation) carried out an aeromagnetic survey (150 metre mean terrain clearance, 1500 metre line spacing, 55 metre sample spacing) for the South Australian Department of Mines and Energy over the western margin of the Murray Basin. Part of the total magnetic intensity data is reproduced in Figure 3. The Black Hill Norite anomaly is characterised by a major negative in the northeast and a slightly reduced positive in the southwest with the principal axis oriented approximately NE-SW. The amplitude of the aeromagnetic anomaly is approximately 3000 nT. Kennedy (1989) identified two other anomalies as being related to the Black Hill intrusion and this has since been verified by drillhole evidence (Turner, 1991).

In regions of low inclinations, and where the magnetisation direction is not known but is clearly different from the local geomagnetic direction, aeromagnetic data cannot be successfully reduced to the pole. Mapping the boundaries of thesource in these cases is difficult and the 3D analytic signal has been proposed as a possible solution (Roest et al., 1992; MacLeod et al., 1993; Qin, 1994).

The Black Hill magnetic anomaly provides an ideal data set to test the application of the analytic signal. Its resultant magnetisation direction is known and it can therefore be reduced to the pole (though the shallow inclination does pose a problem). Its 3D analytic signal can also be computed and tested against the known extent of the intrusive acquired from outcrop, drillhole and gravity data.

The BMR aeromagnetic profile data were projected onto a 300 metre by 300 metre grid. The magnetic data were reduced to the pole (resultant vector declination and inclination are approximately 211° and -5° respectively). The 3D analytic signal was computed from the gradients, which are admittedly crude because of the grid cell size. Nevertheless, the reduced-to-the-pole map (Figure 4) is similar to the analytic signal map (Figure 5). The trace of the analytic signal high covers the known extent of the intrusive. The reduced to the pole anomalies roughly match the residual gravity anomalies confirming the accuracy and pervasiveness of the measured NRM. In addition, the similarities between the analytic signal map and the reduced to the pole map demonstrate the effectiveness of the analytic signal in locating the source of the magnetic anomaly.

Reduction to the pole is not a straightforward operation at low latitudes.Additionally, even when mathematically possible, the operation may not transform all anomalies successfully, as the direction of magnetisation in different sources from the same geographic region may be quite different as a result of remanence. There are a number of magnetic granites in the vicinity of the Black Hill Norite, none of which appear to exhibit any NRM. Their magnetic anomalies are distorted in the reduced to the pole map but preserved in the 3D analytic signal map. Note too that the correct computation of the analytic signal is critically dependent on how accurately the magnetic gradients can be calculated.

DISCUSSION

Rock magnetism studies are critical to the successful interpretation of aeromagnetic data. The results of these studies can be used to build up a rock property database which can be used to extend the interpretation to regions where rock magnetism analysis cannot be undertaken.

The Black Hill Norite is an excellent palaeomagnetic recorder because it appears to contain only one NRM component which is thermal in origin, and because there is good evidence to suggest that it has not been deformed or metamorphosed since its intrusion. Its application in fixing the Early Ordovician palaeomagnetic pole position for Australia arose from the recognition by aeromagnetic interpreters that its unusual magnetic anomaly implied a strong remanent component.

Demagnetisation and hysteresis measurements show that the Black Hill Norite contains magnetite and low-Ti titanomagnetite grains with a bimodal size distribution. The susceptibility is mainly attributable to relatively large MD grains with a lesser contribution from SD grains, whereas the remanence is dominated by ultrafine SD grains. The presence of substantial amounts of high coercivity, high unblocking temperature SD grains accounts for the palaeomagnetic stability, the intense remanence and the high Koenigsberger ratio. The magnetic mineralogy has been verified by results from preliminary optical and electron microscopy.

The analytic signal method can be successfully applied to the interpretation of magnetic data from regions of low magnetic inclinations, or where the magnetisation direction is not known but is clearly different from the local geomagnetic direction. Despite the regional nature of the Black Hill Norite aeromagnetic data, the similarities between the analytic signal map and the reduced to the pole map demonstrates the effectiveness of the analytic signal in locating sources of magnetic anomalies.

ACKNOWLEDGMENTS

This project was funded by the Australian Research Council under the Small Grants scheme and by the Science Faculty of the University of Adelaide.

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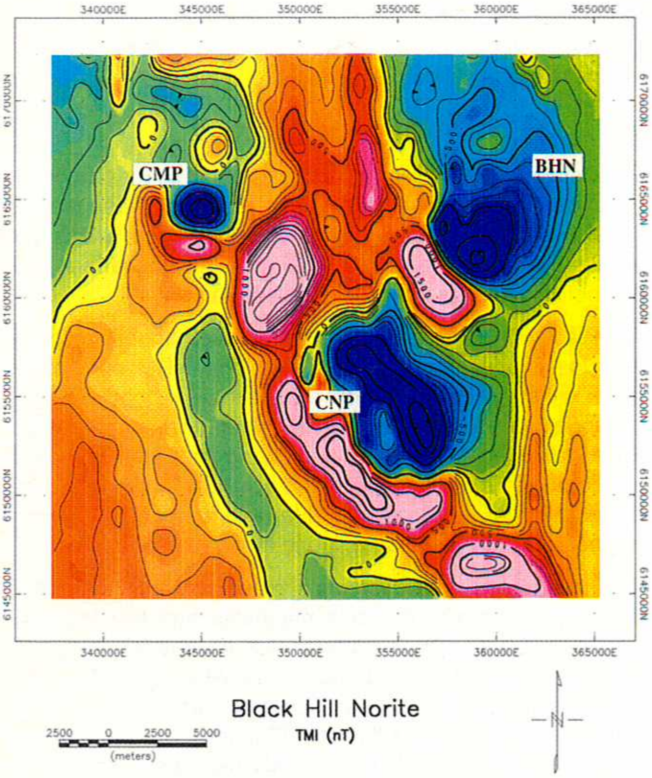

Fig. 3. Total magnetic intensity map of part of the western margin of the Murray Basin, including the anomalies caused by the Black Hill Norite (BHN), Central Pluton (CNP) and Cambrai Pluton (CMP). The CNP and CMP are gabbroic intrusions related to the Black Hill Complex. Magnetic values are in nanoTeslas.

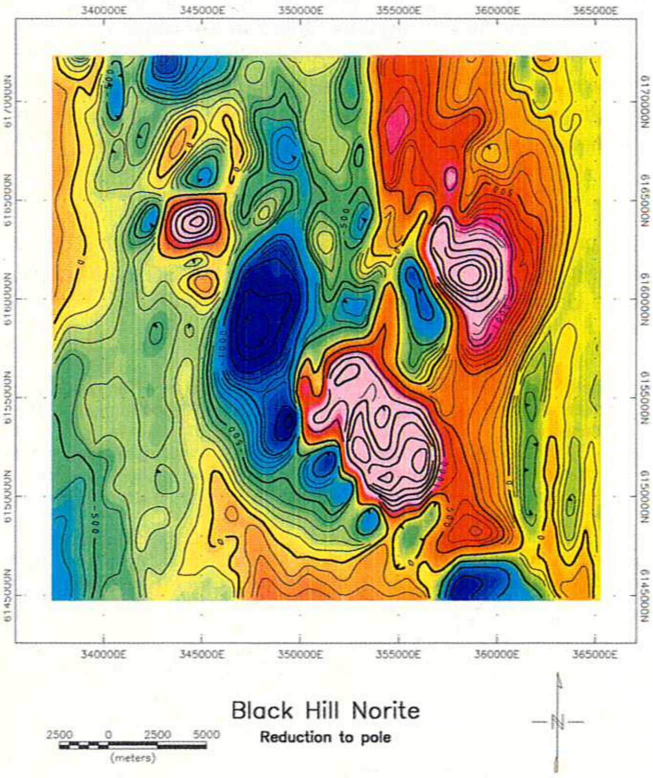

Fig. 4. The magnetic anomalies of the Black Hill Norite have been reduced to the pole in this map (anomalies in nanoTeslas).

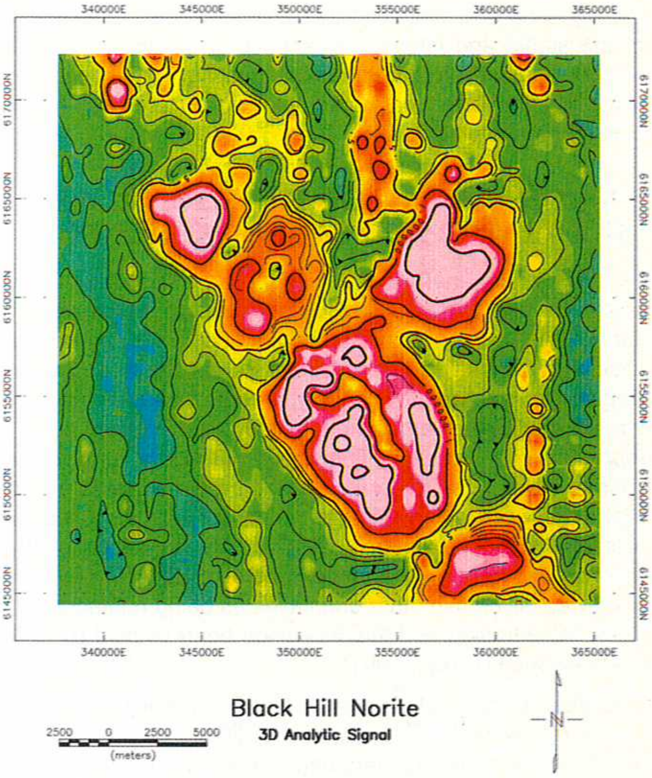

Fig. 5. The 3D Analytic Signal transformation applied to the total magnetic intensity grid data (units of nT/m).

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