Exploration Geophysics (1993) 24, 209–212

MRF 786

Rock magnetism and geophysical interpretation of the Black Hill Norite, South Australia

Shanti Rajagopalan
Department of Geology and Geophysics
University of Adelaide
Adelaide, SA 5005

Phillip Schmidt
CSIRO Division of Exploration and Mining
PO Box 136
North Ryde, NSW 2113

David Clark
CSIRO Division of Exploration and Mining
PO Box 136
North Ryde, NSW 2113

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 Norite gives rise to an unusual magnetic anomaly, a major negative to the north-east with a similar positive to the south-west, which is atypical of the present magnetic inclination of -65° and declination of +8°. Measurements of natural remanent magnetization on oriented samples revealed a high magnetic susceptibility (2000 to 5000*10^{-5} SI units) and a very stable remanent magnetization with the following properties: declination 221.2°, inclination 7.6° (α_{95}=4°) and a Koenigsberger ratio of approximately 2. The Black Hill Norite is inferred to have formed at equatorial latitudes. Surface measurements are probably representative of the rock at depth since forward modelling incorporating remanent magnetization gave a good match between observed and modelled magnetic anomalies.

Key words: Delamerian Orogeny, Black Hill Norite, natural remanent magnetization, magnetic anomaly

Introduction

The Black Hill Norite, found 83 km ENE of Adelaide (Fig.1), is believed to have intruded during the Ordovician period. It gives rise to a 3000 nT magnetic anomaly which has a strong negative peak in the north-east and a similar positive peak in the south-west. Since the anomaly could not be explained by the local magnetic inclination and declination, it was obvious that the rock must carry a strong component of natural remanent magnetization (NRM) quite different from that of the present field. This prompted a study of the rock magnetism of the Black Hill Norite. An added interesting aspect was that the palaeomagnetic pole position derived from the Black Hill Norite study could be critical to the construction of the Ordovician part of the apparent polar wander path for Australia (see Schmidt *et al.*, this volume).

Geology

Sediments of the Adelaide Supergroup and overlying Kanmantoo Group (Fig.1) were deformed and metamorphosed during the Delamerian Orogeny, about 505 Ma. Igneous rocks found in the southern Adelaide Fold Belt can be classified with respect to the orogeny as being either of pre-, syn- or post-tectonic origin. 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.

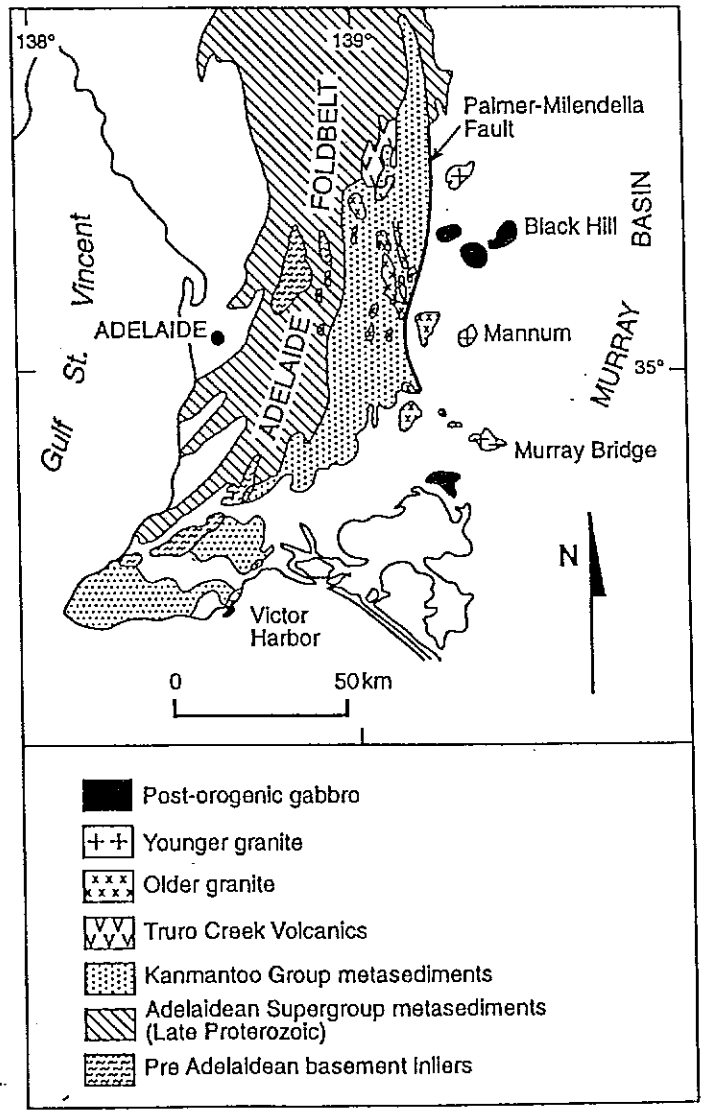

FIGURE 1
Simplified geological map of part of the Adelaide Fold Belt. The western margin of the Murray Basin, together with the Palmer-Milendella Fault Zone, and relevant intrusives are shown.

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

The exposed granites and gabbros are undeformed and their intrusion is believed to have marked the cessation of the Delamerian Orogeny. They may have originated through extended fractionation of basaltic magmas, and appear to be compositionally and spatially distinct from the deformed granites (pre- and syn-tectonic) found in the Adelaide Fold Belt (Sandiford *et al.*, 1992; Turner *et al.*, 1992a,b). This bimodal post-tectonic igneous suite suggests a period of extensional tectonics very shortly after the close of the Delamerian Orogeny. Magmatism increased with the intrusion of several plutons at Black Hill which consist of undeformed, layered gabbros. Basaltic dykes cut the Black Hill Norite and Mannum Granite and are believed to slightly postdate these intrusives.

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 (Fig.1). It is not metamorphosed and observed deformation is restricted to discrete shear zones and it 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±5 Ma and they also gave a K-Ar date on biotites of 486 Ma indicating there has been no significant thermal perturbation subsequent to crystallization. A seven point Nd-Sm mineral-whole rock isochron (Turner, 1991) yielded an age of 489±10 Ma.

The Black Hill complex comprises several large layered plutons with a continental tholeiitic nature. At Black Hill the range of lithologies extends from peridotites and troctolites through olivine gabbros and norites to gabbro-norites and pyroxene monzonites as well as late dyke-like equivalents of the post-tectonic granites. Geochemistry indicates that the Black Hill gabbros resulted from a mantle-derived tholeiitic magma which evolved via plagioclase + olivine and plagioclase + pyroxene fractionation combined with concomitant crustal assimilation.

The opaque minerals (Turner, 1991) found in the Black Hill Complex include pyrite, hemo-ilmenite and magnetite (sometimes with exsolved hercynite). 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 Black Hill Norite magnetic anomaly

The Bureau of Mineral Resources (now the Australian Geological Survey Organisation) carried out an aeromagnetic survey (150 metre mean terrain clearance, 1500 metre line

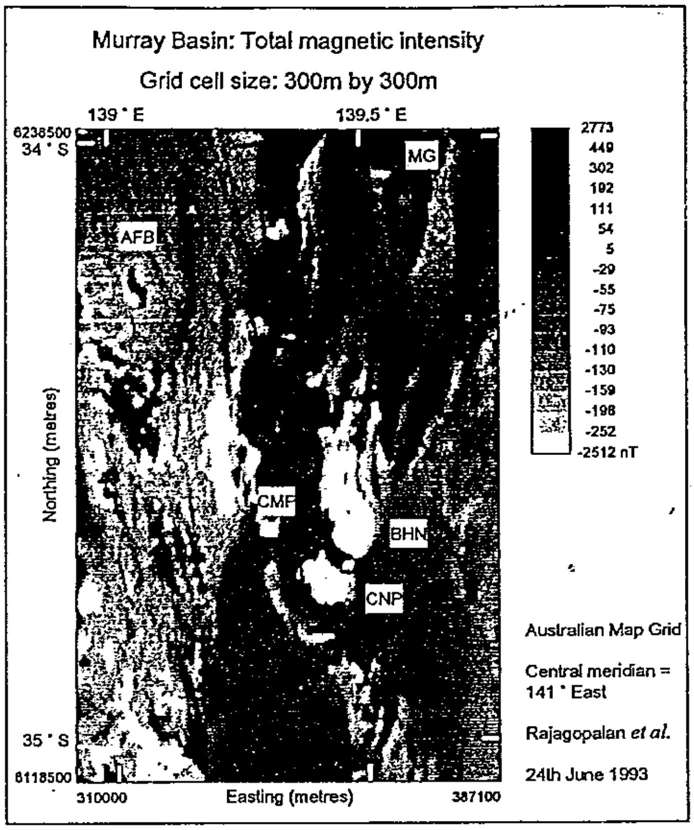

FIGURE 2
Total magnetic intensity map of the western margin of the Murray Basin including the anomalies caused by the Adelaide Fold Belt (AFB), Morgan Gabbro (MG), Black Hill Norite (BHN), Central Pluton (CNP) and Cambral Pluton (CMP). The Morgan Gabbro anomaly consists of a circular high and a triangular low.

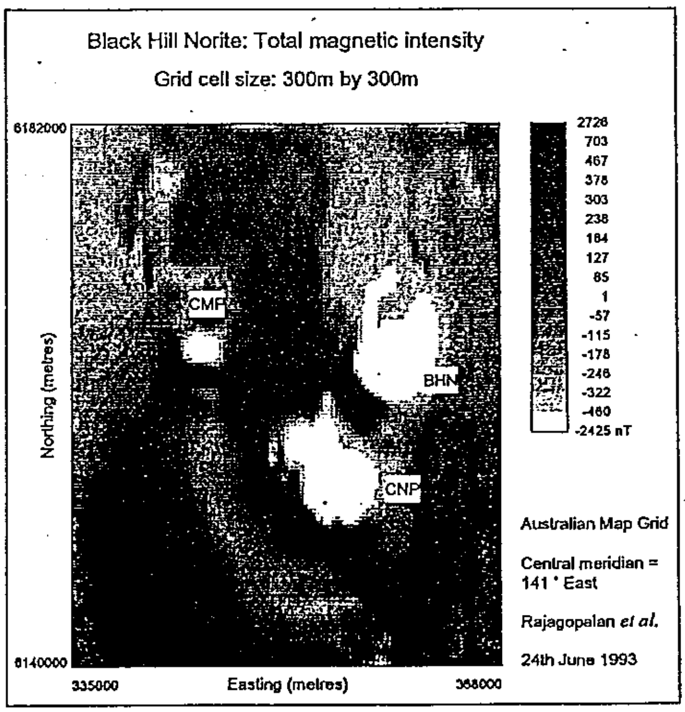

FIGURE 3
Total magnetic intensity map of the magnetic anomalies caused by the Black Hill Norite (BHN), Central Pluton (CNP) and Cambral Pluton (CMP). The Black Hill Norite and Central Plutons are characterized by a large low in the NE and a high in the SW. The Cambral Pluton is slightly different in that its high-low axis is N-S.

spacing, 55 metre sample spacing) for the South Australian Department of Mines and Energy over the western margin of the Murray Basin in 1978. Part of the total magnetic intensity data is reproduced in figure 2 and a subset, the Black Hill Norite magnetic anomaly, in figure 3. This anomaly is characterized by a major negative in the north-east and a slightly reduced positive in the south-west with the principal axis oriented NE-SW. The anomaly amplitude exceeds 3000 nT. There are at least two similar anomalies in the vicinity: a smaller anomaly in the west and a larger one to the southwest. Though neither source is exposed, gabbroic rocks were intersected in drill-holes into both anomalies. The smaller source was named the Cambrai Pluton and the larger one the Central Pluton (Kennedy, 1989).

For a funnel-shaped source or vertical pipe at this latitude (approximately 35°S, ambient magnetic field inclination -65° and declination +8°) the total magnetic intensity anomaly resulting from induced magnetization alone should consist of a major magnetic high to the north and a much smaller low to the south. The principal magnetic axis (or the high-low axis) should trend north-south, though this might be affected by the elongation direction of the source. This is in fact the kind of anomaly caused by another gabbro, the Morgan Gabbro, which occurs nearly due north of Black Hill (top right of figure 2) and lies 300 metres below the surface. It has not been dated or sampled for rock magnetism studies. It is likely to be a post-tectonic intrusive. However, since its magnetic anomaly does not appear to contain a strong remanent component, the Morgan Gabbro is either a poor palaeomagnetic recorder or of a different age to the Black Hill Norite.

Gravity data collected by the South Australian Department of Mines and Energy and Adelaide University (Kennedy, 1989; Turner, 1991) shows that the Black Hill and Cambrai plutons are associated with residual gravity highs (60 μms^{-2} and 50 μms^{-2} respectively). Kennedy (1989) interpreted the sources to be funnel-shaped and extending to a depth of around 3 to 3.5 km. The density of gravity stations is not sufficient for rigorous modelling.

Rock magnetism results

The anomalous magnetic signature of the Black Hill Norite has been known for some time (D.M. Boyd, *pers. comm.*, 1986). Wake-Dyster (1974) used a vertical field magnetometer to measure the direction of the natural remanent magnetization. Though his measurements were scattered he derived the mean estimates of the declination and inclination of the remanent magnetization to be 212° and 23° respectively. Intensity could not be measured by this method though he indicates that the remanent intensity is of the same order as that of the present earth's field. This, of course, is an estimate of the natural remanent magnetization without any cleaning procedures or demagnetization applied to the samples.

Study of oriented samples collected for rock magnetism (see Schmidt *et al.*, this volume) shows a very stable remanent magnetization: declination 221°, inclination 8°, intensity 4.94 A/m, susceptibility 0.049 SI and a Koenigsberger ratio of 2.1. Outcrop susceptibility measurements ranged from 2000 to $5000 \cdot 10^{-5}$ SI units. Only one component of natural remanent magnetization was detected. Demagnetization to various degrees resulted in a reduction of the NRM intensity but the direction remained relatively constant (this explains the good agreement with Wake-Dyster's results). From these results it can be concluded that the Black Hill Norite contains both multidomain and single or pseudo-single domain grains of magnetite. The high susceptibility is a result of multidomain magnetite which may represent 1% to 2% of the rock volume, while the stable and intense NRM is carried by single domain or pseudo-single domain magnetite. The NRM is probably a thermal remanent magnetization acquired during cooling of the Black Hill Norite. Subsequent to its intrusion, the Black Hill Norite has had a stable geological history and it is unlikely that it has been significantly heated or deformed.

The principal magnetic axis of the Central Pluton anomaly is parallel to that of the Black Hill Norite anomaly which indicates a similar resultant magnetization direction. However, the magnetic axis of the Cambrai pluton anomaly is oriented N-S rather than NE-SW indicating that its resultant magnetization direction may be slightly different from that of the other two gabbros. In the absence of any rock magnetism data from these non-exposed rocks, the possibility remains that the plutons have similar remanent directions, with different Koenigsberger ratios resulting in different total magnetization directions.

Modelling of magnetic anomalies

The available aeromagnetic data have been reinterpreted using the rock property information. The magnetic data were reduced to the pole on the basis of a resultant vector with a declination and inclination of approximately 229° and -20° respectively. The reduced-to-the-pole anomalies matched the residual gravity anomalies confirming the accuracy and pervasiveness of the NRM. However a resultant inclination of -45° was sufficient to convert the Cambrai Pluton magnetic anomaly such that its magnetic anomaly matched its gravity anomaly. This supports the previous observation that the Cambrai Pluton resultant magnetization direction might be different to that of the Black Hill and Central Plutons.

Preliminary forward modelling (see figures 4 and 5) revealed that it was possible to incorporate the available rock magnetization information within geologically realistic models and arrive at a reasonable match between observed and modelled data. Surprisingly, however, a knowledge of the rock magnetism alone does not appear to be sufficient to resolve the 3-dimensional structure of the intrusives. The Black Hill Norite anomaly could be quite successfully modelled as a sphere! This is probably because the vertical petrologic layering described by Turner (1991) is reflected in its magnetic properties, i.e. the magnetic anomaly is caused by the upper gabbroic layers. An intrusive source with limited depth extent may be considered equivalent to a dipole or sphere model. Interference from neighbouring sources is probably the most significant impediment to satisfactory modelling of the anomaly. At present the available gravity data are insufficent to resolve its shape and a gravity survey has been planned so that the gravity model may be used to constrain the magnetic models.

Discussion

The Black Hill Norite has a strong natural remanent magnetization component with a shallow inclination indicating that it was intruded at equatorial latitudes. The single remanent component indicates that the NRM is probably primary thermal remanent magnetization. The known amount of relatively coarse-grained (probably multidomain) pure magnetite present is sufficient to explain the high magnetic susceptibility. The stable and intense remanence is probably caused by fine-grained pure magnetite (i.e. single or pseudo-single domain) exsolved out of pyroxenes and/or feldspars though this needs to be verified by electron probe work. The rock property information measured on surface samples can be taken to be representative of the rock at depth since both reduction to the pole and forward modelling based on these measurements produced satisfactory results.

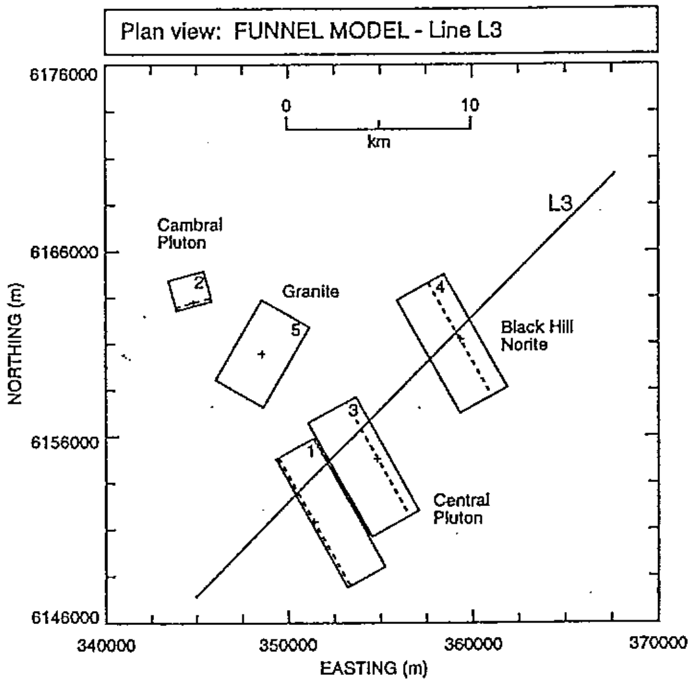

FIGURE 4
Plan view of the line modelled in figure 5 and the projected cross-section of the different models used.

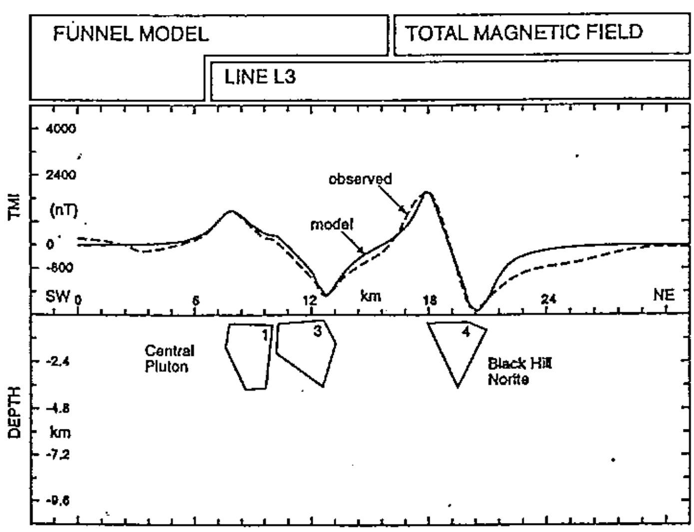

FIGURE 5
Modelled aeromagnetic grid profile. All models are flat-topped and their horizontal cross-section is rectangular. The vertical cross-section tapers downwards to simulate a funnel-shaped intrusive. The modelled profile includes the effect of the Black Hill Norite, Central Pluton, Cambrai Pluton and the granite (not shown) which lies in between the Central and Cambrai Plutons. Three axes are shown: the vertical cross-section (DEPTH), the magnetic anomaly axis (TMI) and the distance along the profile.

Acknowledgements

This project was funded by the Australian Research Council under the Small Grants scheme.

References

Bontenakel A., (1992), 'Three-dimensional modelling of the Truro-Sandleton area using aeromagnetics and gravity', *B.Sc. (Hons.) Thesis (unpubl.), University of Adelaide,* pp25.

Brown C.M., Tucker D.H. and Anfiloff V., (1988), 'An interpretation of the tectonostratigraphic framework of the Murray Basin region of southeastern Australia, based on an examination of airborne magnetic patterns', *Tectonophysics,* **154**, 309-333.

Kennedy R.J., (1989), 'A 3-D gravity and aeromagnetic interpretation of the Black Hill-Cambrai region', *B.Sc. (Hons.) Thesis (unpubl.), University of Adelaide,* pp30.

Milnes A.R., Compston W. and Daily B., (1977), 'Pre- to syn-tectonic emplacement of early Palaeozoic granites in southeastern South Australia', *J. Geol. Soc. Aust.,* **24**, 87-106.

Rajagopalan S., (1989), 'Aeromagnetic interpretation of the Kanmantoo Group, South Australia', *Ph.D. Thesis (unpubl.), University of Adelaide,* pp128.

Sandiford M., Foden J., Zhou S. and Turner S., (1992), 'Granite genesis and the mechanics of convergent orogenic belts with application to the southern Adelaide Fold Belt', *Trans. Roy. Soc. Edinburgh: Earth Sciences,* **83**, 83-93.

Turner S.P., (1991), 'Late-orogenic, mantle-derived, bimodal magmatism in the southern Adelaide Foldbelt, South Australia', *Ph.D. Thesis (unpubl.), University of Adelaide,* pp196.

Turner S.P., Foden J. and Morrison R.S., (1992a), 'Derivation of some A-type magmas by fractionation of basaltic magma: an example from the Padthaway Ridge, South Australia', *Lithos,* **28**, 151-179.

Turner S., Sandiford M. and Foden J., (1992b), 'Some geodynamic and compositional constraints on "postorogenic magmatism"', *Geology,* **20**, 931-934.

Wake-Dyster K., (1974), 'The investigation of the magnetic characteristics of the Black Hill Norite, western Murray Basin', *B.Sc. (Hons.) Thesis (unpubl.), University of Adelaide,* pp25.

Wegmann D., (1980), 'Pre-Tertiary geology of the Black Hill region in the western Murray Basin of S.A., with special emphasis on the petrology and geochemistry of the gabbroic rocks', *B.Sc. (Hons.) Thesis (unpubl.), University of Adelaide,* pp26.