Inversion of anomalies due to remanent magnetisation: an example from the Black Hill Norite of South Australia

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Inversion of anomalies due to remanent magnetisation: an example from the Black Hill Norite of South Australia

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There has been a recent renewal of interest in estimation of magnetisation direction for improved magnetic field interpretation. In this study we review practical issues of recovering magnetisation direction using magnetic moments of the causative body. We also investigate the recovery of magnetisation directly from multi-stage inversion of magnetic field data. We apply these methods to the well-studied magnetic anomalies over the Black Hill Norite of South Australia. Both magnetic moment analysis and inversion recover consistent magnetisation directions, and these can be used in further studies to estimate geological structure. The magnetisation directions agree closely with measured remanent magnetisation directions. This implies that the anomalies are principally due to the remanence of a high Koenigsberger ratio (Q).

KEY WORDS: magnetic, moment, anomaly, remanent, magnetisation, inversion.

INTRODUCTION

Computation of the magnetic field due to a source body requires specification of the strength and orientation of its magnetisation. The magnetisation is a vector resultant of an induced magnetisation parallel to the local geomagnetic field and a remanent magnetisation of generally unknown direction. Prediction of remanent magnetisation is difficult as it can be acquired at different stages in the history of the rock and rotated in subsequent tectonic events. Direct measurement of remanent magnetisation is also problematic as it requires multiple oriented samples to provide a representative estimate of the magnetisation of a complete rock mass. Several authors have addressed this problem, including Roest & Pilkington (1993) and Li et al. (2004), but despite these efforts, most magnetic-field interpretations proceed on the unqualified assumption that the effects of remanent magnetisation are insignificant, and only for anomalies that demonstrably cannot be caused by an induced-only magnetisation is the presence of remanent magnetisation invoked. The non-uniqueness of potential field inversion allows that remanent magnetisation may pass undetected in many magnetic-field interpretations with the consequence that estimates of other parameters such as the location, shape and dip of source bodies are also in error.

Magnetic-moment analysis (Helbig 1963; Andersen & Pedersen 1979; Valyashko et al. 1995; Schmidt & Clark 1997, 1998; Phillips 2005; Phillips et al. 2007; Caratori Tontini & Pedersen 2007, 2008) provides a direct method for the estimation of magnetisation direction from the magnetic field itself. It is therefore a desirable aspect of all magnetic-field interpretations, if only to confirm that magnetic anomalies are indeed caused by a magnetisation parallel to the geomagnetic field. Schmidt & Clark (1998) emphasised the value of this analysis and the suitability of present-day computational power to apply the analysis and resolve magnetisation direction. Phillips (2005) has developed a method of scanning a TMI grid and recovering magnetisation direction estimates screened for consistency across adjacent windows and windows of different sizes.

HELBIG’S INTEGRALS AND THE DIPOLE MAGNETIC MOMENT TRANSFORMATION

Consider a compact magnetic source centred at $(x_c, y_c, z_c)$ with uniform (parallel) magnetisation $\mathbf{J} = (J_x, J_y, J_z)$ and whose anomalous magnetic field is $\Delta \mathbf{B}(\mathbf{r}) = [\Delta B_x(\mathbf{r}), \Delta B_y(\mathbf{r}), \Delta B_z(\mathbf{r})]$. Then, the zero order magnetic dipole moment $M_0$ of the source body is given by the relation (Medeiros & Silva 1995; Caratori Tontini & Pedersen 2008):

$$M_0 = \iiint_V J(r')dV$$

where $\mathbf{r}' = (x', y', z')$ is the position vector of a volume element $dV$ within the magnetised source and where the x, y, z coordinates are defined within a right-hand clockwise (NED) coordinate system, i.e. x-N, y-E, z-D, which is identical to the IGRF coordinate system. Furthermore, Helbig (1963) has shown that the magnetic dipole moment $\mathbf{M}_0 = (M_x, M_y, M_z)$ of the disturbing magnetic source may be evaluated from integral moments of the anomalous magnetic field $\Delta \mathbf{B}(\mathbf{r})$ at all
points \( r = (x, y, z_0) \) on the horizontal plane \( z = z_0 \). In this instance the two horizontal components \( M_x, M_y \) of the zero order magnetic dipole moment \( \mathbf{M} \) are the first-order geometric moments of \( \Delta B_x(r) \), about the \( x, y \) axes respectively whereas the vertical component \( M_z \) of the magnetic dipole moment \( \mathbf{M} \) is the first-order geometric moment of either \( \Delta B_x(r) \) or \( \Delta B_y(r) \) about the \( x, y \) axes respectively. These relations between the zero order dipole moment of the magnetised body and the first-order geometric moments of its anomalous magnetic field may be expressed through the following double integrals; namely, for the \( M_e \) moment we have:

\[
M_e = -\frac{1}{(2\pi)} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} x\Delta B_e(x, y, z_0) \, dx \, dy \quad (2a)
\]

and for the \( M_y \) moment

\[
M_y = -\frac{1}{(2\pi)} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} y\Delta B_e(x, y, z_0) \, dx \, dy \quad (2b)
\]

and finally for the \( M_z \) moment

\[
M_z = -\frac{1}{(2\pi)} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} x\Delta B_e(x, y, z_0) \, dx \, dy \quad (2c)
\]

or alternatively

\[
M_z = -\frac{1}{(2\pi)} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} y\Delta B_e(x, y, z_0) \, dx \, dy \quad (2d)
\]

Furthermore, it is also noted that the following pair of integrals are identically zero (see Helbig 1963)

\[
I_{xby} = \frac{1}{(2\pi)} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} x\Delta B_y(x, y, z_0) \, dx \, dy = 0 \quad (2e)
\]

and also,

\[
I_{ybx} = \frac{1}{(2\pi)} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} y\Delta B_x(x, y, z_0) \, dx \, dy = 0 \quad (2f)
\]

In addition to the above expressions, it is noted that the zero-order geometric moments of the anomalous magnetic field due to the disturbing body are all identically zero, namely

\[
I_{0bx} = \frac{1}{(2\pi)} \int_{-\infty}^{+\infty} \Delta B_x(x, y, z_0) \, dx \, dy = 0 \quad (3a)
\]

and

\[
I_{0by} = \frac{1}{(2\pi)} \int_{-\infty}^{+\infty} \Delta B_y(x, y, z_0) \, dx \, dy = 0 \quad (3b)
\]

and

\[
I_{0bz} = \frac{1}{(2\pi)} \int_{-\infty}^{+\infty} \Delta B_z(x, y, z_0) \, dx \, dy = 0 \quad (3c)
\]

By inspection of Equations (2a)–(2d), it is noted that the magnetic dipole moment \( \mathbf{M} \) is completely determined from measurements of a single pair of magnetic-field components, i.e. either from \( \Delta B_x(x, y, z_0) \), \( \Delta B_y(x, y, z_0) \) or from \( \Delta B_y(x, y, z_0) \), \( \Delta B_z(x, y, z_0) \). In practice, however, a more stable estimator of the vertical component \( M_z \) of the magnetic moment is

\[
M_z = \left[ \frac{M_{x(x)} + M_{y(y)}}{2} \right] \quad (4a)
\]

where \( M_{x(x)} \) and \( M_{y(y)} \) are given by Equations (2c) and (2d) respectively. Also, a further necessary condition for the computation of a reliable magnetic moment is that the integrals in Equations (2e) and (2f) are both approximately zero, namely,

\[
I_{xby} \gg I_{ybx} \gg 0 \quad (4b)
\]

Other magnetic moment components that can be derived are the horizontal moment,

\[
M_H = \left[ M_x^2 + M_y^2 \right]^{1/2} \quad (5a)
\]

and the total magnetic moment \( M_T \),

\[
M_T = \left[ M_x^2 + M_y^2 + M_z^2 \right]^{1/2} \quad (5b)
\]

Furthermore, the declination \( D_m \) and inclination \( I_m \) of the magnetic moment vector \( \mathbf{M} \), and also the declination \( D_{res} \) and inclination \( I_{res} \) of the magnetisation vector \( \mathbf{J} \) (since \( \mathbf{M} \) and \( \mathbf{J} \) are parallel vectors) are given by

\[
D_m = D_{res} = \arctan \frac{M_y}{M_x} \quad \text{for } 0 \leq D_m < 2\pi \quad (5c)
\]

\[
I_m = I_{res} = \arctan \frac{M_z}{M_x} \quad \text{for } -\pi/2 \leq I_m \leq \pi/2 \quad (5d)
\]

It is noted that in addition to the direction of magnetisation which is obtained from the zero-order magnetic moment vector \( \mathbf{M} \), other information including the position or centre magnetisation of the anomalous body and its orientation may be estimated from the first- and second-order magnetic moments respectively (see Medeiros & Silva 1995).

**MAGNETISATION ESTIMATES FROM MAGNETIC MOMENT ANALYSIS OF INCOMPLETE ANOMALIES**

Many magnetic-field anomalies occur in clusters, and a common interpretation problem is to separate overlapping anomalies from each other. For each anomaly, this is generally a compromise between selecting a larger subset of data with some contamination from adjacent sources, or a smaller subset with incomplete sampling of the anomaly of interest. Most techniques to separate anomalies utilise differentiation to sharpen the anomalies, and the fact that magnetic moment analysis involves integration can be expected to intensify problems arising from imperfect anomaly separation. Schmidt & Clark (1998) proposed an estimator to correct the reduction in magnitude of the magnetisation estimated from magnetic moment analysis due to
truncation of the anomaly but did not present the effect of truncation on the recovered estimate of the direction of magnetisation.

Phillips (2005) developed various techniques of estimating magnetisation direction by scanning anomalies with a window-based magnetic moment analysis and then searching the resulting estimates to find directions consistent within a region and between windows of different sizes. It is clearly appropriate to dismiss magnetisation directions that are inconsistent across small distances, but the converse question of how well spatial consistency qualifies a magnetisation direction requires further investigation. There are three concerns with magnetic moment analysis of partial anomalies. First, there is distortion of the estimated magnetic-field component values supplied to the analysis by Fourier transform of the clipped TMI data. Second, there is the question of how well the analysis itself copes with access to only part of the anomaly in many cases off-centred with respect to the source body, and third there is the problem of the discrete 2D Fourier integral transform, but its practical application is always performed using the discrete Fourier transform. Unfortunately, however, the integral and discrete Fourier transforms are only distantly related, and it is therefore unwise to consider the two transforms as being equivalent.

To investigate the suitability of magnetic moment analysis to the investigation of incomplete anomalies, we first applied the analysis to synthetic data generated by forward computation with a known magnetisation direction. Figure 1 shows the TMI anomaly computed from the induced magnetisation of a spherical source at a geomagnetic inclination of $-50^\circ$. Widths of the windows used to scan this grid for the analysis are indicated in Figure 1 together with centre locations of the windows. A magnetic moment analysis was performed both on magnetic-field components computed directly from the source model and on field components derived by Fourier transform of the TMI grid as outlined by Blakely (1995) and Schmidt & Clark (1998). Figure 2 is an image of the spatial distribution of magnetisation direction estimates derived by the analysis at the two window sizes. For this particular anomaly with a north–south-oriented magnetisation, the error in declination arises predominantly from applying the analysis in windows with an east–west offset from the source location. Conversely, errors in inclination arise predominantly from north–south offsets of the window from the source location. These patterns will be different for different magnetisation directions, and recognition of characteristic patterns might provide a means of refining or confirming magnetisation direction estimates.

Close to the source location, error in magnetisation direction increases with offset at approximately twice the rate for the small window as for the larger window.

**Figure 1** Synthetic TMI anomaly (inclination $-50^\circ$, declination $0^\circ$) used to test scanning with magnetic moment analysis. The source body location is shown in purple. Points indicate centres at which the analyses were performed, and the squares indicate the range of window sizes used.
There are also greater errors in the FFT analysis for the smaller window, so that analysis with larger windows seems preferable provided this does not introduce field variations from adjacent sources to contaminate the magnetisation estimates.

For this synthetic study we confirm that the closest agreement in magnetisation direction between co-centred windows of different size is close to the source where the magnetisation estimate is approximately correct. Unfortunately, however, the extent of the close agreement between the magnetisation directions encompasses a considerable range of magnetisation directions from different window sizes and is not a precise indicator of the best magnetisation direction. Furthermore, as is evident from Figure 2, the true magnetisation direction occurs in an area where there are rapid changes in the estimated magnetisation direction.

Figure 3 shows contours of the discrepancy in estimated magnetisation direction overlaid on images of the modulus of the analytic signal (AS) of TMI and of reduced to pole TMI (RTP). The AS has a low sensitivity to magnetisation direction and is commonly used to locate small source bodies or the margins of wider bodies. However, as shown in Figure 3, for this mid-inclination geomagnetic field, the offset of the peak AS of TMI from the source body is too great to use it to locate a reliable magnetisation direction estimate. The AS of RTP, also shown in Figure 4, does correctly locate both the source body and the coincident best magnetisation value, but this is of limited practical value, as knowledge of magnetisation direction is required to perform the RTP transform.

From these studies with a synthetic magnetisation, we conclude that while consistency between magnetisation directions from different window sizes provides approximate estimates of the true magnetisation direction, that those estimates may be in error by 20° or more. We also conclude that windows as large as possible should be used to provide more stable and reliable estimates of magnetisation direction.

INVERSION OF THE MAGNETIC ANOMALIES OVER THE BLACK HILL NORITE

Geology and petromagnetic considerations

The Black Hill Norite or the Black Hill Gabbroic Complex is an undeformed, post-tectonic mafic intrusion which was emplaced during the Ordovician period some 487 ± 5 Ma ago (Turner 1991). It was intruded into metasediments of the Cambrian Kanmantoo Group, which were deformed and metamorphosed during the Delamerian Orogeny (ca 515–493 Ma; Burtt & Purvis 2002). Lithologies within this mafic complex include gabbro, olivine gabbro, gabbro-norite, anorthosite, norite, troctolite, peridotite, diorite and quartz diorite. The Black Hill Norite has been interpreted as a suite of alkali or A-type mafic intrusives of continental tholeiitic association (Turner 1991).

Figure 4 shows TMI variation over the Black Hills Norite with a substantial range of about 3000 nT. The anomaly shapes are quite different from those expected for induced anomalies and lead inescapably to the conclusion that the magnetisations are dominated by remanence components oriented obliquely to the present geomagnetic-field direction. These anomalies are very close to each other, and...
analysis of their magnetisation directions requires their separation.

The Black Hill Norite magnetic anomalies have attracted several previous studies. For example, Rajagopalan et al. (1993) report a rock magnetic study and a magnetic interpretation of the Black Hill Norite, while Schmidt et al. (1993) have conducted a paleomagnetic study. Rajagopalan et al. (1993) report magnetic susceptibilities in the range 0.02–0.05 SI units and a moderate Koenigsberger ($Q$) ratio of approximately 2.1. The high susceptibility is due to the presence of multidomain magnetite grains between 1 and 3 vol%.

The intensity of the natural remanent magnetisation (NRM) was 4.9 A/m, and its direction was determined as declination 221.2°N and inclination 7.6° (Rajagopalan et al. 1993; Schmidt et al. 1993). This NRM is highly stable and is thought to be a thermo-remanent magnetisation that is carried by single domain and pseudosingle domain grains of magnetite, which occur within grains of plagioclase and clinopyroxene (Rajagopalan et al. 1993; Schmidt et al. 1993). The ilmenites occur both as individual grains and also as exsolved intergrowths with magnetite in biotite. The presence of hemo-ilmenite is interesting because it too may carry a stable remanent magnetisation known as lamellar remanent magnetisation (see McEnroe et al. 2002).

**Estimation of magnetisation directions**

Schmidt & Clark (1997) applied magnetic moment analysis to the cluster of anomalies shown in Figure 4 and obtained a direction of declination 209°, inclination −32°, only 22° different to the magnetisation direction obtained by vector summation of the NRM and induced magnetisation using the measured $Q$ factor of 2.1. Phillips (2005) performed a magnetic moment analysis of the same section of TMI data by scanning the grid in windows of different size. Phillips reported stable magnetisation direction estimates for the four anomalies annotated in Figure 4 as listed in Table 1. Phillips accepted the resultant magnetisation direction presented by Schmidt & Clark (1997) as the true magnetisation direction and quoted the departure of his derived magnetisation directions from that as a measure of error in his analysis.

Figure 5 shows the AS image corresponding to the TMI image of Figure 4. From inspection of this image, we suggest that the northern margin of Anomalies A and B may be a sheared contact (indicated by the red line in Figure 5), that some structures can be traced into the anomalies and that the north–south fold-belt trends to the west and east of this cluster of anomalies are deflected around the intrusive bodies. These interpretations of the AS image suggest that the intrusions are not completely post-tectonic, as has been assumed from the lack of deformation fabric in their limited outcrops, and this may in turn influence interpretation of the remanent magnetisation directions.

Anomaly C is sufficiently compact that it appears as a single high in the AS image. Peaks in the AS image over the broader anomalies A, B and D are interpreted to indicate the approximate margins of their source bodies. Inspection of Figures 4 and 5 suggests that anomaly A may be a composite of several smaller anomalies, each with a dominant TMI central low and a lesser high to its...
southwest. Consequently, we have treated this anomaly as being due to multiple source bodies of identical magnetisation direction. Anomaly B has the same general pattern with a dominant central low and a positive to the south and west. Within anomaly B, there are marked differences between the sharp gradients and

Figure 4 TMI anomalies (nT) over the Black Hills Norite. Polygons show clips applied in magnetic moment analysis of the various anomalies.
high amplitudes to the southwest and the weaker gradients and lower amplitudes to the northeast. We interpret these differences to be due either to lateral variation in composition or to a plunge or thinning of the body towards the northeast. Anomalies A, B and C have broadly similar anomaly patterns, and we expect a

Figure 5 Modulus of the Analytic signal to TMI with interpreted shear (red).
limited scatter of magnetisation directions from them, but Anomaly D is a single-signed, positive anomaly and is due to a differently directed magnetisation.

The magnetisation direction estimates for sources of anomalies A to D derived by magnetic moment analysis of the clip areas drawn in Figures 4 and 5 are listed in Table 1. The directions are also plotted on an equal-angle stereonet projection in Figure 6. The corresponding directions estimated by Phillips (2005) are also listed in Table 1 and plotted in Figure 6.

The resultant (NRM plus induced) magnetisation direction calculated by Schmidt & Clark (1997) and used by Phillips (2005) was based on sampling of limited

Table 1 Magnetisation directions (MM magnetic moment).

<table>
<thead>
<tr>
<th>Anomaly</th>
<th>Declination</th>
<th>Inclination</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>232</td>
<td>−11</td>
<td>MM Scan (Phillips 2005)</td>
</tr>
<tr>
<td>A</td>
<td>230</td>
<td>25</td>
<td>MM analysis (this study)</td>
</tr>
<tr>
<td>A</td>
<td>225</td>
<td>24</td>
<td>Inversion (this study)</td>
</tr>
<tr>
<td>B</td>
<td>234</td>
<td>−4</td>
<td>MM Scan (Phillips 2005)</td>
</tr>
<tr>
<td>B</td>
<td>237</td>
<td>30</td>
<td>MM analysis (this study)</td>
</tr>
<tr>
<td>B</td>
<td>238</td>
<td>28</td>
<td>Inversion (this study)</td>
</tr>
<tr>
<td>C</td>
<td>273</td>
<td>26</td>
<td>MM Scan (Phillips 2005)</td>
</tr>
<tr>
<td>C</td>
<td>233</td>
<td>12</td>
<td>MM analysis (this study)</td>
</tr>
<tr>
<td>C</td>
<td>232</td>
<td>8</td>
<td>Inversion (this study)</td>
</tr>
<tr>
<td>C</td>
<td>223</td>
<td>6</td>
<td>MM scan (this study)</td>
</tr>
<tr>
<td>All</td>
<td>209</td>
<td>−2</td>
<td>MM analysis (Schmidt &amp; Clark 1997)</td>
</tr>
<tr>
<td></td>
<td>221</td>
<td>8</td>
<td>Paleomagnetic measurement (Rajagopalan et al. 1993)</td>
</tr>
<tr>
<td></td>
<td>209</td>
<td>−32</td>
<td>Resultant induced and remanent (Schmidt &amp; Clark 1997)</td>
</tr>
<tr>
<td></td>
<td>223</td>
<td>9</td>
<td>Paleomagnetic intermediate temperature (Schmidt et al. 1993)</td>
</tr>
<tr>
<td></td>
<td>231</td>
<td>20</td>
<td>Paleomagnetic high temperature (Schmidt et al. 1993)</td>
</tr>
</tbody>
</table>

Figure 7 Cross-section views of the preferred model for anomaly C.
Figure 8 TMI measured (top) and computed from the preferred plate model (bottom) with the body outline.

Figure 9 Perspective view of the best plate and ellipsoid models with the TMI anomaly shown for reference.
outcrop, and it is difficult to know how well these measurements represent the main, buried rock mass which is giving rise to the anomalies. However, our magnetisation estimates quite closely match the rema-
nence directions, and we suggest that this is consistent with the sources having a significantly higher Q factor than the measured value of 2.1. High Q factors are not uncommon for such rock types (e.g. Clark 1997).

**Figure 10** Inversion misfit statistic for a range of resultant magnetisation directions. The diamond represents the preferred model, which has the same magnetisation direction but different shape to the best-fitting model.

**Figure 11** Two and 3 km window frames and centre points on the TMI image.
Staged inversion of Anomaly C

We selected anomaly C, which is the simplest and best separated of the anomalies to test recovery of magnetisation direction by inversion. We first digitised a source body to the AS anomaly and then ran an inversion with only depth and magnetisation set free. This produced a magnetisation direction in reasonable agreement with the value from magnetic moment analysis. To test sensitivity of the estimated magnetisation direction to the position of the source body we imposed offsets of the source body of 1 km to east, west, south and north. At each position repeat inversions converged to magnetisation directions on average 45° different to the best-estimated direction. We would expect errors of no greater than 200 m in positioning a source body, which should correspond to an error of about 10° in estimated magnetisation direction.

We then set free both the position and magnetisation of those mispositioned bodies and the inversions converged consistently to within 0.1° in magnetisation direction and 2 m in horizontal position. This consistency is clearly not a measure of accuracy because there are many common dependencies on model assumptions and anomaly definition, but it proves the ability to recover at least a repeatable magnetisation direction by inversions with widely different starting-points.

In a subsequent inversion we set free the body shape and size parameters. This inversion produced considerable changes in body shape and significant improvements in matching the field with only minor rotations of the magnetisation direction. The model with the smallest misfit was a dipping sheet, but from geological considerations we prefer a sheet or plug with subvertical edges. Our preferred model has a goodness of fit only marginally poorer than the best-fitting body. Cross-sections through the model are shown in Figure 7, and the measured and computed fields are shown for comparison in Figure 8.

To investigate the influence of body shape, we repeated the staged inversion process using an ellipsoid source with a different modelling algorithm. The ellipsoid model plotted in Figure 9 is virtually coincident with the plate model and has a magnetisation only 1° different. This difference is not a measure of error, as both models use common anomaly selection, regional/residual separation and assumptions of a compact, homogeneous source. Our best estimate of

Figure 12 Magnetisation estimates from magnetic moment analysis in a 3 km window. ‘A’ is the location of the interpreted best magnetisation estimate. ‘B’ and ‘C’ are locations of minima in differences between 2 and 3 km window estimates.
Figure 13 Error estimate (percent) from the magnetic moment analysis in the 3 km window (top) and angular difference (degrees) between 2 and 3 km window magnetisation directions (bottom).

Figure 14 RTP derived with a magnetisation of declination $222^\circ$ inclination $10^\circ$ (top) and modulus of the analytic signal computed from that RTP with a contour overlay of the difference of the 3 km window magnetisation estimates from that direction (bottom).
magnetisation direction from inversion studies of declination 232°, inclination +9° is only 4° different to the estimate from magnetic moment analysis (also based on the same anomaly separation).

To determine sensitivity in recovering magnetisation direction we systematically tested different magnetisation directions. These not only produced systematically poorer fits to the data as plotted in Figure 10 but also required shallow-dipping bodies which we believe are less geologically acceptable. These results confirm that, as reported by Foss (2006), staged inversions are able to recover consistent magnetisation direction from a magnetic anomaly. The validity of that magnetisation direction, however, depends on the validity of the separation of the anomaly from other field variations.

Magnetic moment scan of Anomaly C

We scanned both the measured and computed anomaly C grids with magnetic moment analysis performed in square windows of side length 2 and 3 km centred on points as plotted in Figure 11. The resulting magnetisation directions are plotted in Figure 12. Almost identical directions derived from the measured and computed grids confirm that in sufficiently large windows, the longer wavelength variations, which are best matched in the inversion process, are more significant in derivation of the magnetisation direction than are the shorter wavelengths, which differ between the two grids.

Schmidt & Clark (1998) developed an error estimate based on over-prescribed solution of the Helbig integrals. This statistic plotted in Figure 13 shows an elongate east-west minimum across the centre of the interpreted source body. Also plotted in Figure 13 is the angular separation between the magnetisation estimates derived from the 2 and 3 km side-length windows. Ideally this separation would show a minimum coincident with that of the error statistic and thereby indicate the location of the best magnetisation direction estimate, but instead it gives two widely separated minima marked as points ‘B’ and ‘C.’ The magnetisations corresponding to these minima are different by over 30°, and neither is suitable to explain the anomaly.

We consider the magnetisation directions derived by magnetic moment analysis of the complete anomaly, inversion of the anomaly and magnetic moment analysis from scanning the anomaly with a 3 km side-length window to be essentially identical with no firm grounds for discriminating between them. Figure 14 shows an RTP of the anomaly calculated using a magnetisation direction of declination 222°, inclination 10°. The single-signed positive expression of the anomaly and its co-location with the inversion model is taken as a further confirmation of the magnetisation direction. Also shown in Figure 14 is the AS of the RTP with a contour overlay of the angular separation between the magnetisation direction and that estimated from the 3 km side-length window. This image shows a general agreement with the corresponding image in Figure 3 from the synthetic data study. A further illustration of the consistency between the magnetic moment analysis and inversion studies is provided by Figure 15 which shows a close correspondence between the edge of the source model and an image interpretation of that edge provided by the edge filter (Shi & Butt 2004) computed from the RTP derived with the estimated magnetisation direction.

CONCLUSIONS

Magnetic moment analysis and staged inversion recover consistent magnetisation directions from the same residual anomaly, but both methods are dependent on selection of that data by interpretive separation from
other magnetic-field variations. Application of magnetic moment analysis to windowed subsets of an anomaly recovers approximate magnetisation directions when applied directly above the source body, but magnetisation directions derived from windowed subsets should be treated with caution. We have been surprised at the consistency with which magnetisation direction can be recovered with well-constructed inversion strategies. The resulting ability to estimate the direction of magnetisation allows geological structure to be recovered from inversion of magnetic-field data. With the Black Hills Norite magnetic-field data we have been able to determine the location, shape and depth of source bodies, which we could not have done without the capability to resolve the magnetisation direction. Our magnetisation directions are consistent with measured remanent magnetisation directions, and we suggest that the anomalies may be due to bodies of particularly high Q factor such that the resultant magnetisation direction is not significantly rotated from the remanent magnetisation direction.

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