Introduction

Reliable targeting of deep magnetic sources from inversion of aeromagnetic or ground magnetic survey data is difficult, as those measurements are only in the distal field. New boreholes provide access for magnetic field measurements much closer to source. If these measurements can be made during the drilling program, they enable re-direction of boreholes which might otherwise miss their target. Even after completion of an intersecting borehole, the inversion of such measurements is of considerable value in improving the planning of further boreholes, and reducing the number of boreholes required to map-out the body. Present borehole gradiometry uses either TMI sensors (e.g. Zhang et al, 2007) or a set of 3 component sensors (e.g. Silva and Hohmann, 1981). A single string of down-hole TMI data is of limited value in vectoring towards a source. Three component data is potentially more informative, but is subject to extreme requirements in precision of orientation, primarily because of the penalties in miss-orientation of the main geomagnetic field components. The magnetic field gradient tensor substantially compensates for the limited spatial distribution of borehole measurements, with much less demanding orientation requirements (because the geomagnetic field produces only small gradients). To illustrate the advantage of measuring the magnetic gradient tensor, Figure 1 shows two source bodies, with identical magnetization direction, to either side of a borehole, which produce almost identical TMI signatures in that hole. However, as shown in Figure 2, the magnetic gradient tensor measured in the hole overcomes this ambiguity (in this case particularly the $B_{xx}$ and $B_{yy}$ channels), and would support vectoring towards the true target.

![Figure 1](image1.png)

**Figure 1** Two sources, with identical magnetization direction, to either side of a borehole, which produce near-identical TMI variation in that hole.

![Figure 2](image2.png)

**Figure 2** The magnetic gradient tensors for the sources and borehole illustrated in Figure 1.
We report here a synthetic model investigation of down-hole magnetic tensor gradiometry undertaken as part of a project to build a down-hole magnetic tensor gradiometer, and to develop the software to invert the data in near-real time. The gradiometer is based on a concept by Tillbrook (2004), rotating vector sensors (presently anisotropic magneto-resistors) about their perpendicular axis, with frequency separation applied to split the signal into field component and gradient terms. Functions have been derived to vector towards separated magnetic sources from multi-channel magnetic gradient tensor (e.g. Wilson 1985, Beiki et al, 2012, Clark 2012) but for more general application we have chosen to develop multi-channel inversion algorithms.

**Synthetic cube/sphere model study**

![Synthetic model study](image)

**Figure 3** Vertical boreholes which narrowly miss co-centred sphere and cube model magnetic sources. Green sectors indicate the location of data suitable for whole-body inversion, purple sectors represent the location of data dominated by adjacent segments of the bodies.

**Figure 4** Vertical gradient of TMI a) 350 metres and b) 50 metres above the top face of the cube.
To illustrate the resolution capabilities of borehole magnetic tensor gradiometry, we consider the problem of discriminating between co-centred sphere and cube sources in vertical boreholes which narrowly miss the bodies, as illustrated in Figure 3. The sphere and cube are co-centred. Figure 4 shows vertical gradient of TMI contours in the horizontal plane over the two models at surface, 350 metres above the top of the cube, and within the ground at 50 metres above the top of the cube. The difference between the two vertical gradients of TMI at surface is very slight, and does not support discrimination between the models. The corresponding vertical gradients at the deeper level would readily support discrimination between the models, but can at best be sampled at points where boreholes intersect this surface, and it would clearly take many intersections to recover an approximate mapping. Let us consider instead data acquired in boreholes.

Figure 5 shows the gradient tensor elements down a vertical borehole adjacent to the NW edge of the cube model. Just as with single channel TMI data, individual elements do not uniquely constrain the location and distribution of magnetization (particularly if the direction of magnetization is also unknown), but additional channels carry additional information. Over a short segment of the borehole, where the tensor measurements can first be expected to have a useful signal to noise ratio, inversion of the full tensor may provide an estimate of the distribution of the magnetization, and also its strength and direction. However, because of the rapid $1/r^4$ decay with distance of the magnetic gradient away from a compact source, together with the trajectory of the borehole towards the magnetization, there are much more abrupt variations in signal strength than we are accustomed to in mapping TMI variations in sub-horizontal planes above a magnetic source. As a consequence, this is likely to be only a short and abrupt transition zone before the measurements are completely dominated by the proximal parts of the magnetization. This characteristic of the data requires particular management of the inversion process, to not allow measurements dominated by a local section of the magnetization to contribute towards mapping of the more distant parts of the magnetization to which they have no effective sensitivity.

Figure 5 The NW borehole gradient tensor (blue – sphere, red – cube, black - difference).

The data traces in Figure 5 show the separate signatures of the cube and sphere models, and also the magnitude of the difference between them. Although the overlap of the volumes of the two bodies is high, and there is almost no difference in their magnetic signature at surface, the difference in the expression of the two models is locally strong in certain channels of the gradient tensor data measured.
close to the body. In this case, this is particularly obvious in the $B_{xx}$ and $B_{zz}$ channels, with the
difference peaking as the borehole passes both the top and bottom near-corners of the cube, which
extend beyond the sphere model close to this borehole. The strong differences between the magnetic
expression of the two models indicate sections of the borehole where the measurements are dominated
by the proximal parts of the model. Conversely, the preceding sections, where there are similar
expressions of both models, indicates sections of the borehole from which the magnetic gradient data
supply information about the overall distribution of magnetization. Inversion algorithms must be self-
adaptive to estimate this transition in information content, and switch from inversion of the complete
magnetization distribution where appropriate, to focussing only on the local magnetization
distribution, where that dominates the measurements. Our studies focus on recognition of these
transition zones, which is particularly problematic at low signal to noise ratios.

Conclusions

Magnetic tensor gradiometry provides an effective exploitation of the access provided by a borehole,
to map sub-surface magnetizations from a string of measurements. The rapid fall-off of the magnetic
gradient signal, and the large dynamic range in distance to magnetization of the subsurface
measurements, produce abrupt variations in the measured signal. These data characteristics require
new developments in the algorithms used to invert the data.

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