Magnetic field surveys with a source of known magnetization

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SUMMARY

A three component magnetometer developed to be drawn along a track beside drill core to log its magnetic susceptibility and remanent magnetization has been used to measure the external magnetic field of a palaeomagnetic sample over a survey area of side length 30 cm. The objective is to generate survey data from a source of known magnetization which can be used in testing magnetic field analysis algorithms (specifically those related to determination of source magnetization direction). The 3 component data directly emulates vector component survey data, is readily processed to derive gradient tensor data, and can be combined to generate TMI data. We have recovered measured magnetization directions to within 2° and 7° by inversion of TMI data from two initial test surveys.

Key words: magnetic, survey, magnetization, fluxgate, magnetometer

INTRODUCTION

Methods developed to recover source information from analysis of magnetic field data are generally tested against synthetic data forward-computed from known bodies of specified magnetization. Synthetic noise can be added to this data to better emulate application to survey data. Ideally the methods are also tested in appropriate case-studies for which measured source magnetizations are available. However, because the distribution of magnetization in rocks is highly variable across many scales, few if any case studies provide tight constraints with which to verify results of magnetic field analysis. We have recently developed a 3-component fluxgate magnetometer system which measures magnetic field profiles along the side of drill-core to improve sampling and determination of both the remanent and induced magnetization of that core (Leslie et al., 2015) and we realised that this instrument can also be used to survey magnetic fields over sources small enough that we can directly measure their magnetization in a palaeomagnetic laboratory. These surveys of well-known magnetizations bridge the gap between synthetic computer-generated data and true survey data. Also, because the orientation of the source and its distance from the measurements can be varied, the data supports versatile testing of a range of scenarios, as opposed to aeromagnetic data which for any one case study is only available for a single source magnetization, and (generally) a single flying height and line direction. We have generated vector component data primarily as a source of TMI data. The component data itself has limited direct analogue application because of the difficulty in orienting component data on an airborne platform (Dransfield et al., 2003). However, the component data is also a suitable path to generation of gradient tensor data using the along-profile gradients of the 3 field components. We are currently testing surveys in which we record two sets of profiles with the source slightly offset vertically. This gives us vertical interval gradients of the 3 components and of TMI, and allows us to map 5 of the 6 tensor elements (missing only the cross-line gradient of the cross-line component which we can estimate from the sum of the other 2 diagonal elements).

METHOD

Our magnetometer system uses a Bartington 3-axis fluxgate magnetometer drawn along a carefully engineered track with a sampling interval typically of 0.7 mm. The magnetic source we use is a palaeomagnetic sample, which is a cylinder of approximately 2.4 cm diameter and 2.2 cm height. The sample has a hard remanent magnetization (believed to be carried by lamellar intergrowths of magnetite and hematite) with an intensity of 295 Amperes/m, giving a magnetic moment of 2.9 x10^{-3} Ampere metres^2. To emulate a survey we found it easier to fix the survey track in place (providing a single ‘flight-line’) and to subsequently move the sample, as opposed to a conventional survey where the in-ground source is constant and the survey is generated from a series of offset flight-lines. In the studies described in this paper we also found it more convenient to move the sample in a traverse above rather than below the sensor, but this switch of relative elevation is easily accounted for in analysis of the data. We performed our studies in a magnetically noisy environment within a building with metal girders and heavy electrical equipment. Our instruments are portable and could have been taken to a quiet environment, but the objective was to obtain data with noise levels characteristic of airborne surveys rather than optimised data similar to synthetic computed fields. The 3 orthogonal component sensors are set in a known arrangement within a rectangular block, and that block is drawn about 1 metre along a horizontal track using a winch with a potentiometer mounted to its drive shaft to provide a measure of distance travelled (we are currently experimenting with an improved system with a motor-driven fishing reel and a shaft-encoder). The palaeomagnetic core is placed within a sample holder to reduce perturbations in orientation as it is repositioned for each measurement profile, and the sample holder is moved along a ruler at right angles to the track (Figure 1). For the measurements described in this paper the centre of the core was approximately 6 cm above the sensor, and the sample was moved at 1 cm intervals out to 15 cm to either side of the profile. The profiles were typically 80 cm to 1 metre long, but we discarded data towards the ends which is away from the influence of the source.

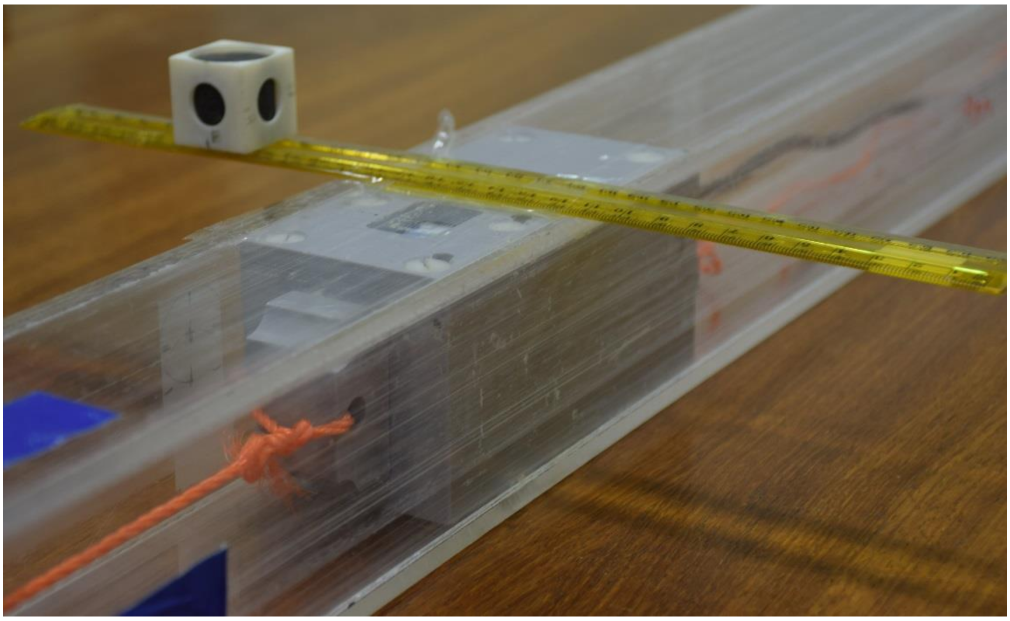

Figure 1 The magnetic source in its holder on a 30 cm ruler, with the 3 component sensor drawn along the measurement profile below.

Figure 2 shows the three-component measurements along a profile directly beneath the source oriented such that the magnetization is approximately vertical up (which causes the B_z magnetic field component to be almost single-signed negative). The shape and amplitude of each component along each profile is a function of the location of the source relative to the profile, and the source orientation (which controls orientation of the overwhelmingly remanent magnetization). Maximum peak-to-trough variations measured for individual components on tracks close to the source were of the order of 3000 nT. Figure 2 shows an expanded amplitude plot of the B_x channel from Figure 1. For this particular combination of profile location and source magnetization orientation, B_x has the smallest range of the 3 components of only 300 nT. There is a short-wavelength (3 mm), low amplitude (maximum 3 nT peak-to-trough) 'chatter' which has very little influence on the recovered signal, and also much longer wavelength (100 to 200 mm) variations of amplitudes up to several tens of nT, which may be due to a combination of imperfections in the track, nearby weak magnetizations in the table on which it is laid, and/or short-period local field perturbations associated with electronics in the building. Some of these longer wavelength disturbances are attenuated with subtraction of the pre-survey and post-survey background field measurements. The most disruptive noise is unattributed line to line base-value and long wavelength variations (not obvious in the individual line data) which were subsequently reduced with conventional tie-line levelling and micro-levelling.

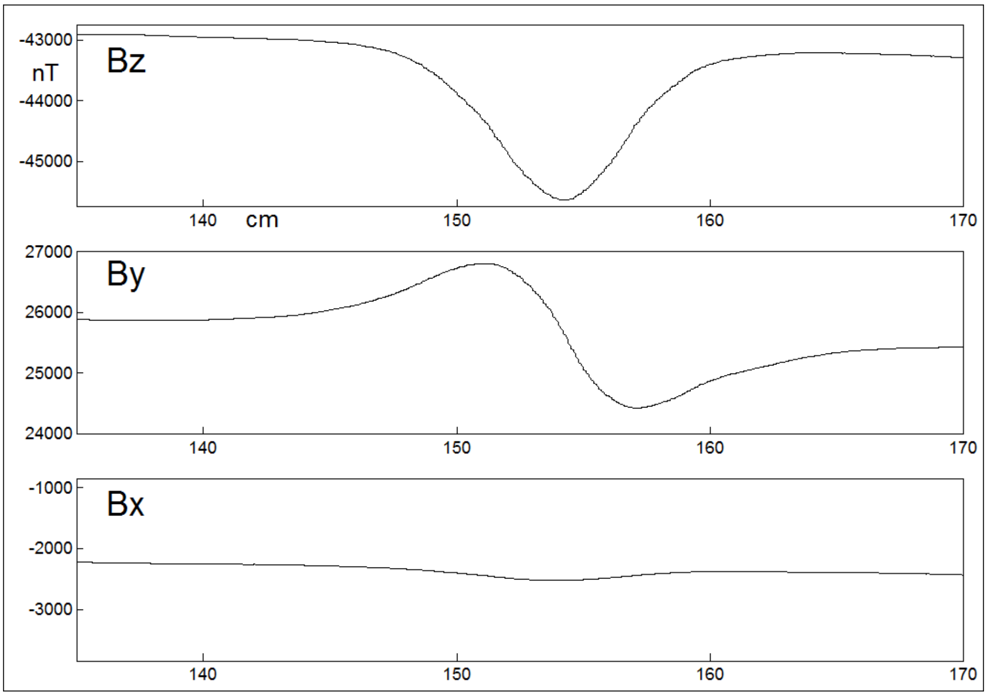

Figure 2 South to north 3 component profile

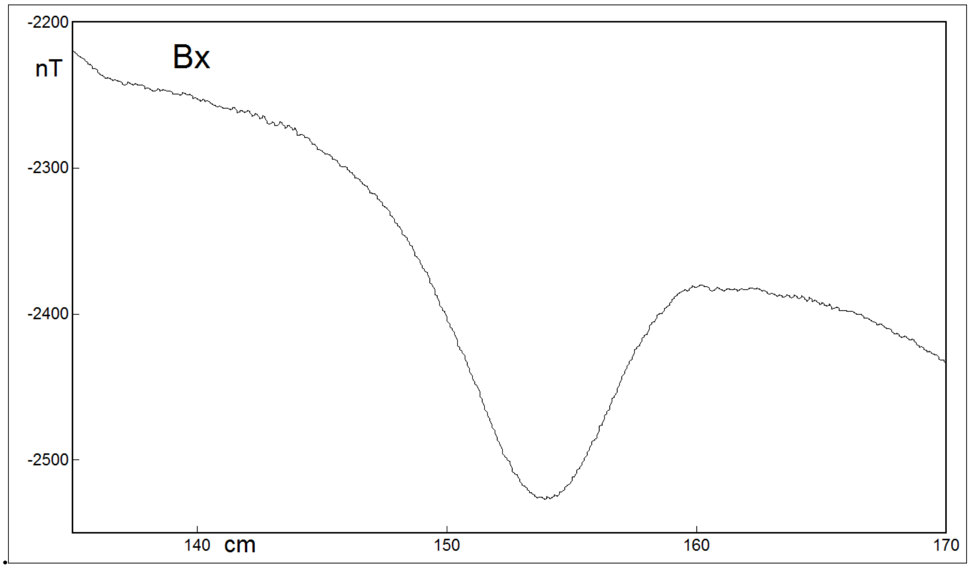

Figure 3 The amplified Bx channel from Figure 2.

DATA PROCESSING

Regional-residual separation of magnetic fields, is generally a major challenge in interpretation of magnetic field survey data, but in this case it is effectively solved by measuring data profiles with no sample present before and after each set of survey measurements, and subtracting the average of those profiles from each survey profile. Ideally this would also reduce the diurnal field variation occurring as each survey is acquired (typically over a 30 minute period), but we found residual line to line shifts of several tens of nT up to over 100 nT, which we attribute to the noisy environment. We kept this 'raw' data for testing algorithms against high noise data. We also cleaned the data with standard tie-line levelling by subtracting level shifts averaged from two tie-lines interpolated though the gridded flight-line data perpendicular to the flight-line direction and located towards the start and end of those lines (away from the source magnetic field). This process reduced but did not eliminate the line to line level shifts. We kept this data for testing algorithms against moderate noise levels, and then cleaned the data further with conventional decorrugation or micro-levelling to give a final low-noise data set, with the micro-levelled data sampled back onto the lines as final data channels. Figure 3 shows images of line-processed, tie-line levelled and microlevelled TMI grids for the survey with the sample oriented to give an approximately vertical-up magnetization. This magnetization is parallel to the local steep geomagnetic field and thereby gives a predominantly positive anomaly (both above and beneath the source). Noise levels varied somewhat from survey to survey. Figure 4 shows TMI grids from one of the cleaner surveys, but even for the noisiest surveys if the full set of flight lines are used in analysis (either directly or via use of generated grids) an effective algorithm should be able to recover magnetization direction quite reliably. We also have the option to remove lines from the data analysis to provide a more sparse coverage, or even to analyse individual profiles. As data coverage becomes less sufficient, the influence of the noise level of the data becomes more critical.

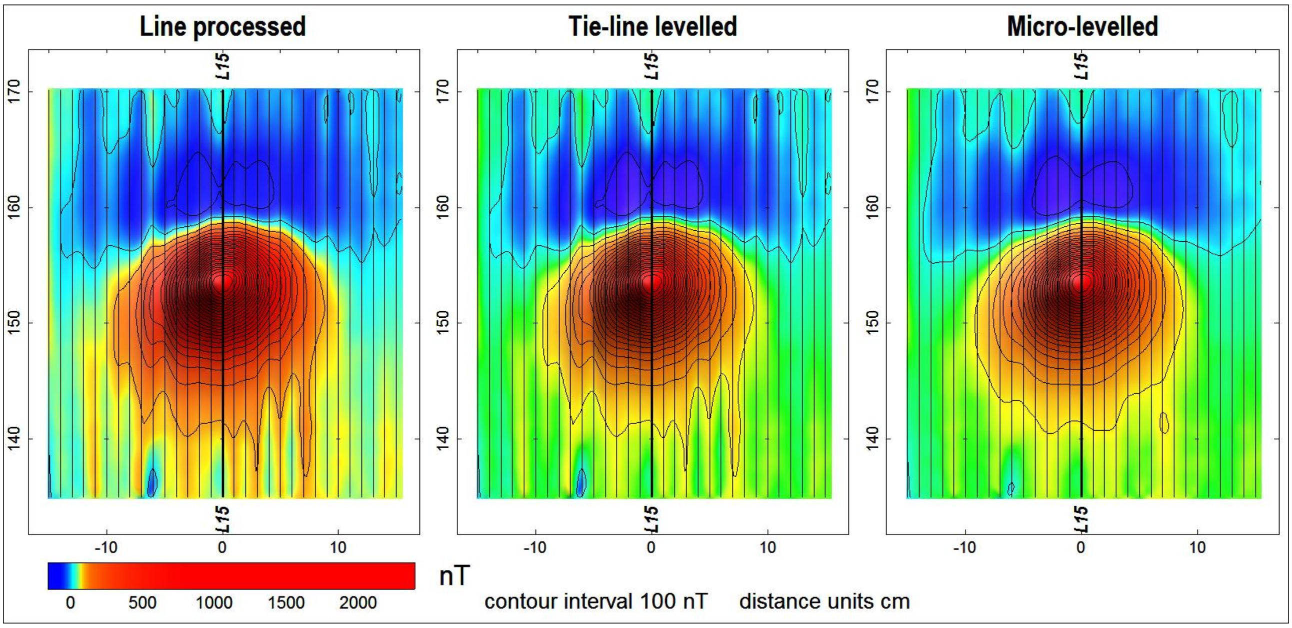

Figure 4 TMI Grids after line processing, tie-line levelling and micro-levelling (magnetization is vertical-up).

Each profile data set consists of line data with 3 separate (B_X,B_Y,B_Z) component channels and a TMI (total magnetic intensity) channel computed from the sum of the squares of the 3 component channels when first measured (before removal of their background fields). During subsequent processing this TMI channel was treated as a 4th channel equivalent to the 3 measured component channels. We could alternatively have completed processing of the individual channels and then computed TMI as a final step, but the approach we used provides a TMI dataset at each processing step. The background field strength and direction were estimated from the averages of each component and of the TMI on each of the background (no-sample) runs. For different surveys the difference in average background value pre- and post-survey varied between less than 10 nT and up to 300 nT. These variations are greater than the expected diurnal variation, and we believe can be attributed to the same local field variations which appear as line to line level shifts in the survey data. However, the apparent declination and inclination values derived from ratios of the estimated background field components were consistent between surveys to within 0.2°. The apparent inclination of -59° is 5° shallower than that computed from the IGRF for the site (which we believe may be due to nearby magnetic sources in the building). We aligned the track approximately north-south using a hand-held compass, and the 5° declination represents a slight misalignment which is well addressed by introducing that declination value into the modelling software, just as is done with conventional survey data to compensate for departures between magnetic and true north.

RESULTS

The final (micro-levelled) TMI data is the most significant output from each survey, as most aeromagnetic field data is currently collected as TMI measurements. The B_X,B_Y,B_Z component grids we measure can be computed from a TMI grid using a 2-d FFT processes (which requires knowledge only of the local geomagnetic field direction - Lourenco and Morrison, 1973). Such grids are used for instance in Helbig (1963) analysis of magnetization direction. Our method of directly measuring the component data provides a test of FFT-derived component data, and an opportunity to substitute between the two in Helbig analysis of a wide range of source magnetization directions. Figure 5 shows the 3-component grids from surveys of the magnetization almost vertical-up, and the reverse magnetization almost vertical-down following a 180° rotation of the core. The magnetization direction is not exactly reversed because the induced magnetization is unaffected by the rotation, but at a Koenigsberger ratio (of remanent to induced magnetization) of over 16, induced magnetization plays only a minor role in generating the external magnetic field. This is evident in the almost perfect reversal pattern between individual component pairs in Figure 5.

The source used in these surveys has a magnetization intensity of 295 Amperes/m, declination 255.7° and inclination -85.1° (in its 'reference' vertical orientation), and a magnetic susceptibility of 0.451 SI. The horizontal and vertical location of the source relative to the survey grid are known, and so we are able to forward compute the expected survey data using magnetic field magnetic modelling software (we used Tensor Technology's ModelVision package to do this). Figure 6 shows the very close match between measured magnetic field variations and those predicted from the source magnetization measurements (which include both remanent and induced contributions). We have also run parametric inversion of the results from the vertical-up and vertical-down magnetizations, and found differences of approximately 5% between measured and inverted magnetization intensities (which can be attributed to small errors in source elevation), and of less than 2° and less than 7° between magnetization directions.

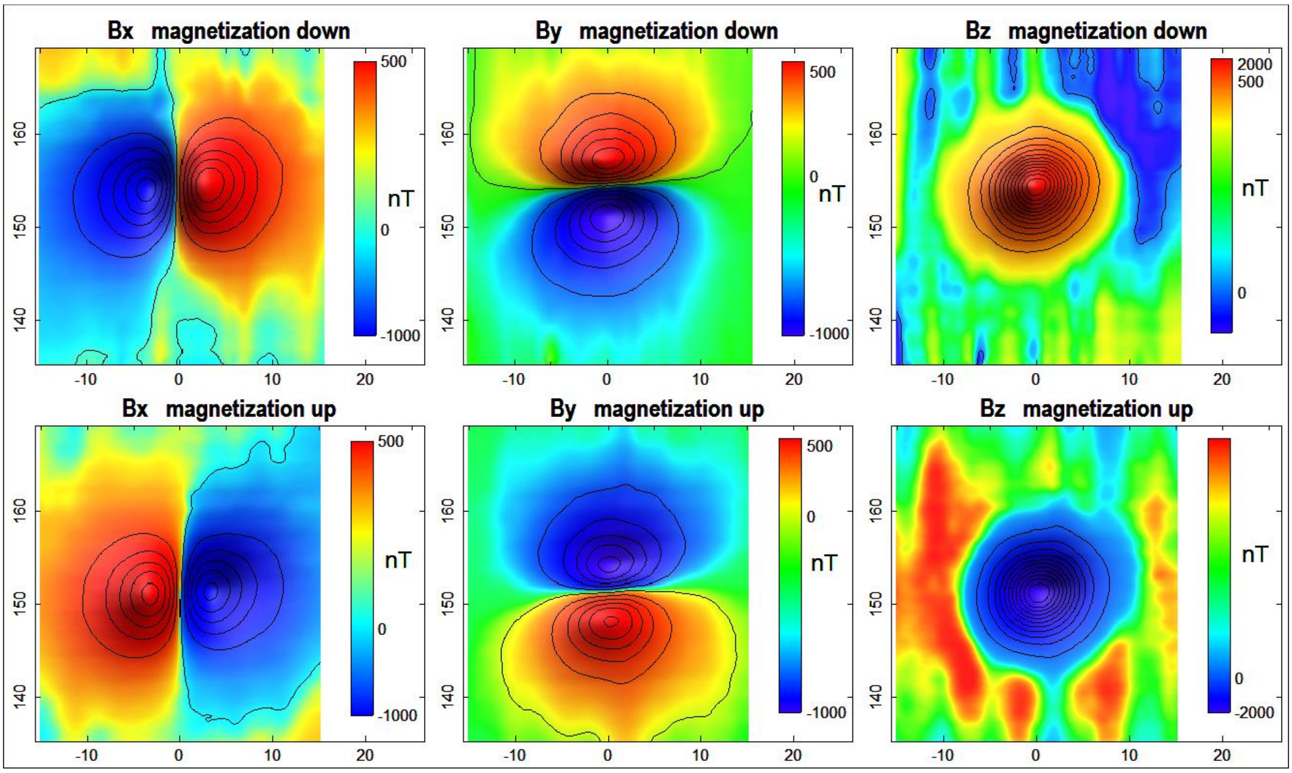

Figure 5 3-component maps for magnetization approximately vertical down (top row) and up (bottom row). Contours 200 nT.

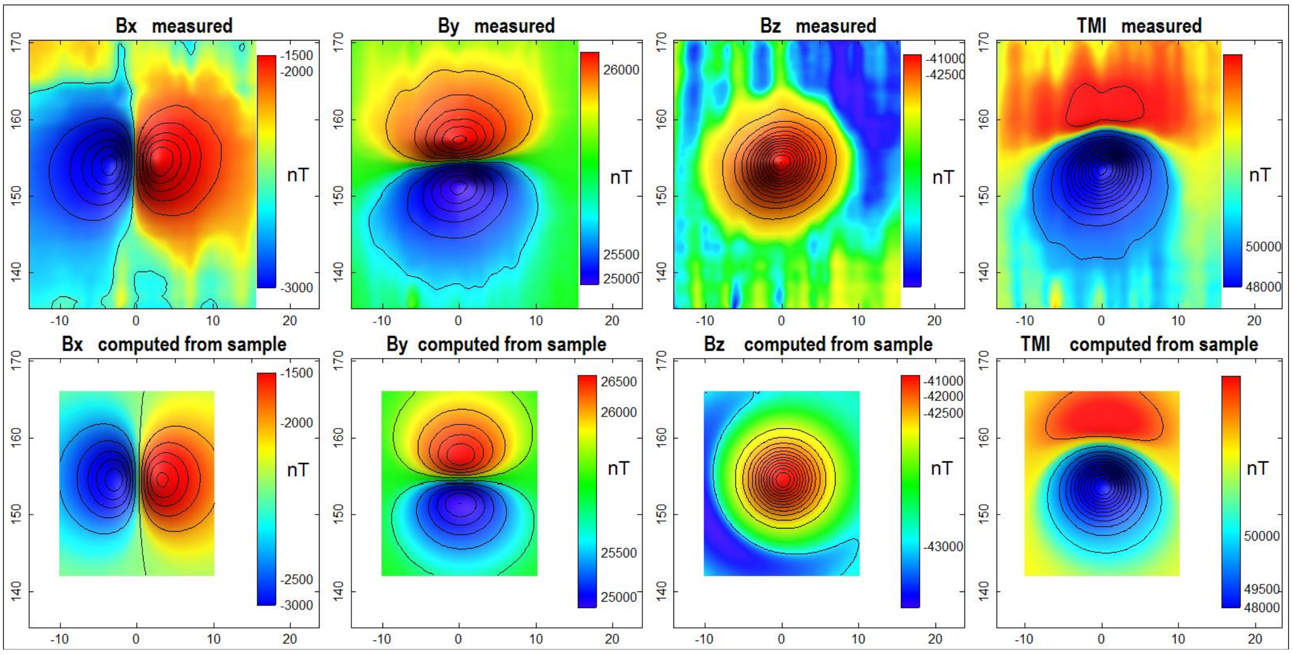

Figure 6 Component and TMI maps measured for downward magnetization (top row) and forward computed from known source magnetization (bottom row). The average background values have been added to the computed components and TMI.

CONCLUSIONS

We have generated three component and thereby TMI data in surveys of a 2.4 cm diameter, 2.2 cm height cylinder of known remanent magnetization and magnetic susceptibility, and have recovered the resultant (remanent plus induced) magnetization to within 2° and 7° by inversion of TMI data from two test surveys. The data will allow us to test new magnetic field analysis algorithms more realistically than with synthetic computed data, and with more confidence than with field survey data for which the source magnetization is rarely if ever well resolved by direct measurement. The data are particularly valuable for testing sensitivity in recovering magnetization direction, because we can generate exactly equivalent survey datasets for steep and low inclination magnetizations. The current results confirm the suitability of our data for testing analysis algorithms for application to field survey data. If at a later time we find the need to upgrade the data we are aware of where improvements can be achieved. Initial results of measuring vertical components are encouraging, and suggest that we will be able to develop analogue tensor survey data with noise levels equivalent to or less than those of tensor data derived from standard aeromagnetic TMI data, but with the advantage that it comes from a source of known magnetization direction.

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