

Influence of self-demagnetization effect on data interpretation in strongly magnetic environments

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SUMMARY

In this paper, we discuss the influence of the self-demagnetization effect on magnetic data and present an alternative means of quantitatively interpreting such data in highly magnetic environments. In particular, we present two important results based on simulation which one might consider in their interpretation of magnetic data when self-demagnetization is present. First, current methods for estimating total magnetization, which are typically applied to the problem of remanent magnetization, do not reliably recover this parameter when the anomalous source bodies have high magnetic susceptibilities. And second, a single value estimation of total magnetization does not provide adequate information to properly resolve subsurface geology through inversion. Numerical experiments demonstrate that directly inverting amplitude data, calculated from magnetic data yet weakly-dependent on magnetization direction, produces superior results when interpreting data generated in terrain with high magnetic susceptibilities.

Key words: magnetics, self-demagnetization, inversion, magnetic susceptibility.

INTRODUCTION

It is commonly accepted that adequate knowledge of true magnetization direction of a causative body is crucial in order to accurately interpret magnetic data by quantitative methods such as inversion. Most currently available algorithms require the knowledge of magnetization direction, since it is an essential piece of information for carrying out the forward modeling (e.g., Li and Oldenburg, 1996; Pilkington, 1997). Such a requirement has been the driving force for development of many well recognized approaches for estimating total magnetization when strong remanence or self-demagnetization are present. Example problems to which these methods are commonly applied include the interpretation of magnetic data over ferrous unexploded military ordnance, banded iron formations, nickel deposits, kimberlite pipes, and depth to basement problems.

In most practical exploration cases, one can simply assume that there is no remanent magnetization and the self-demagnetization effect can be neglected. Consequently, the direction of magnetization is assumed to be the same as the current inducing field direction. This is a valid assumption in

a majority of the cases, as evidenced by many successful applications. However, there are well-documented cases in which such an assumption is inadequate due to the presence of remanence (e.g., Shearer, 2005) and self-demagnetization (e.g., Wallace, 2006).

The difficulties of interpreting magnetic data for these two distinct problems are similar, in some respect, since the magnetization of the causative body will be rotated away from the Earth's inducing field – often drastically. However, the similarities stop there. This is because remanent-magnetization and self-demagnetization have entirely different origins. Remanent magnetization is the net magnetization present in a material in the absence of an external field (Merrill *et al.*, 1996). Remanent magnetization can occur for any magnetic geologic unit and commonly does not have strong dependence on geometry of the source body. Self-demagnetization, in contrast, exists when susceptibilities become large and the magnetic field at a location in the source body is significantly affected by the induced magnetization from neighboring domains (Clark & Emerson, 1999). This process is highly dependent upon the source geometry and the magnetization direction can be much more variable.

The remanent magnetization problem has been well studied and there are two general approaches which have emerged for interpreting magnetic data affected by it. The first is to estimate the direction of total magnetization and supply it to the inversion algorithm (e.g., Dannemiller and Li, 2006), assuming that the magnetization direction does not vary greatly within the target region. Alternatively, one might directly invert amplitude data, a quantity that is calculated from magnetic data but is independent of or weakly dependent of the magnetization direction (Shearer, 2005).

In this paper, we present results of applying these current methods for estimating total magnetization to the less studied problem of self-demagnetization. We likewise demonstrate 3D magnetization distribution models recovered from traditional 3D magnetic inversion that utilizes an estimated total magnetization direction for highly magnetic bodies. We then present the result of applying direct inversion of amplitude data (e.g., Shearer, 2005), calculated from magnetic data yet weakly dependent on magnetization direction. We demonstrate through numerical simulation that the later method provides improved results in recovering shape and orientation of the causative body for high magnetic susceptibilities.

ESTIMATION OF TOTAL MAGNETIZATION DIRECTION

Given the importance of the magnetization direction in the interpretation of magnetic data, it is not surprising that many authors have published on this subject over the past several decades. For example, Zietz and Anderson (1967) have utilized the relationship between locations of the maximum and minimum of an anomaly produced by an anomalous source body. In 1993, Roest and Pilkington presented us with a method in which they correlated the amplitude of the total gradient of the magnetic field and the horizontal gradient of the pseudogravity. Haney and Li (2002) developed an approach for estimating total magnetization for a 2D data set using wavelets. In 2003, Phillips developed a method which utilizes the integral relationships derived by Helbig (1962). Dannemiller and Li (2006) developed a cross-correlation method for estimating magnetization by examining the symmetry of various RTP fields. Currently under development, a group of researchers from Colorado School of Mines and the USGS have shown that the Helbig method for estimating total magnetization direction from magnetic vector components can be extended to tensor magnetic gradient data. These are just a few examples of the work that has been done in estimating total magnetization, and each method carries its own strengths and weaknesses.

The difficulty of working with the estimation techniques, which are overall formulated for and applied to remanent magnetization problems, is that they typically assume the local field is not perturbed significantly within the target region and thus the magnetization direction is approximately constant. While this is valid for many remanent magnetization problems, it is not necessarily satisfied for problems of high magnetic susceptibility where strong self-demagnetization exists. The end example demonstrates application of two established estimation approaches applied to a self-demagnetization problem.

AMPLITUDE INVERSION

Nabighian (1972) showed that the amplitude of an anomalous magnetic field, or the total gradient of the magnetic anomaly vector, is independent of the magnetization direction in 2D problems. While such a property does not extend exactly to 3D problems – thus the absence of a true 3D analytic signal in magnetics – both quantities are only weakly directional dependent. This is especially true for total gradients when the anomaly has been converted to the vertical component by a half reduction to the pole. This property provides the opportunity for direct inversion of the anomaly amplitude or total gradient to recover the magnitude of magnetization without knowing its direction.

Shearer and Li (2004) developed such an algorithm by formulating a generalized inversion using Tikhonov regularization and imposing a positivity constraint on the amplitude of magnetization. The algorithm starts by calculating, for example, the amplitude of the anomalous magnetic field from the observed total-field anomaly. It then treats the amplitude as the input data and recovers the distribution of magnetization as a function of 3D position in the subsurface. One advantage of the approach is that it is not

limited to a single anomaly nor does it require that adjacent anomalies have the same magnetization direction. Therefore the approach is potentially applicable to a wide range of problems where the source distribution is more complicated.

APPLICATION TO SELF-DEMAGNETIZATION PROBLEM

To evaluate the effectiveness of the before-mentioned methods, we utilize a thin, tabular shaped dipping body with varying magnetic susceptibilities. Similar tabular structures exhibiting self-demagnetization are well recognized in exploration for Banded Iron Formations (e.g., Wallace, 2006). The tabular body, Figure 1, is located within a model region spanning 1000m in both northing and easting, and 500m in depth. The body itself strikes north-south with a strike length of approximately 500m. Dip is to the east, with a dipping angle of approximately 30 degrees. The body is assigned magnetic susceptibility values ranging from $\kappa = 1.0$ SI to $\kappa = 10.0$ SI. Data are generated for three susceptibility values ($\kappa = 1.0, 3.0, 10.0$ SI). We note that most geologic problems do not contain susceptibility values greater than $\kappa \sim 3$ SI. The range of susceptibility values above this level lie primarily in the arena of ferrous unexploded ordnance (UXO), which are not considered here.

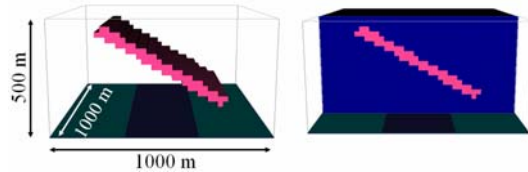


Figure 1: Tabular shaped body for numerical simulations of the effects of self-demagnetization. Susceptibility values are assigned to the model, with values ranging from 1.0 SI to 10.0 SI.

The self-demagnetization effect is calculated for each of the discretized susceptibility models subject to a uniform external field. The solution is obtained by solving an integral equation involving the three components of the magnetization vector in the cells. The external field for this study has amplitude of 50,000 nT, inclination of 65 degrees, and declination of -25 degrees. Data are then computed at an observation height of approximately 1.0 meter above ground, centered over the body and spanning a survey area of 1,500m in both northing and easting. A subset of the data results representing medium, and high susceptibility values are presented in Figure 2 (a-b). For these large susceptibilities, total-magnetization begins to rotate clockwise away from the inducing field and towards the long axes of the tabular body. In response, the measured field likewise begins to rotate clockwise, as shown in Figure 2. To estimate magnetization direction using the Helbig and Cross-Correlation methods, as well as for inverting amplitude data directly for 3D distribution of magnetization, noise is added to each data set with a standard deviation of 5 nT.

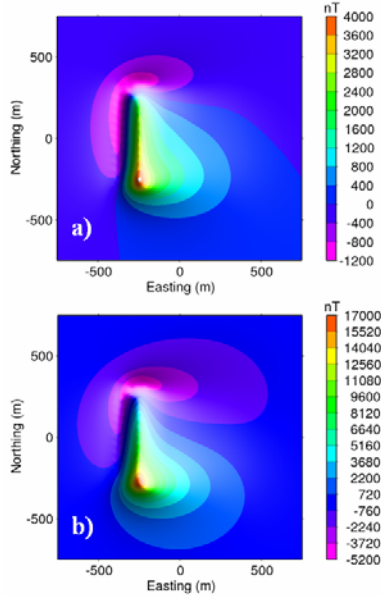


Figure 2: Subset of the magnetic data generated above the tabular shaped body illustrated in Figure 1. The data are generated for susceptibilities of: a) 1.0, and b) 10.0 in SI.

RESULTS

In this section, we present results of two direction estimation methods – Helbig’s method and cross-correlation. Likewise, we also present and compare inversion results in which magnetization direction is supplied to the magnetic inversion algorithm (e.g., Dannemiller and Li, 2006), to the results of amplitude inversion (Shearer and Li, 2004) which directly inverts magnetic amplitude data.

Direction Estimation: Table 1 lists the true and estimated magnetization directions of the tabular shaped body for each susceptibility value. As mentioned previously, the external inducing field has amplitude of 50,000nT, an inclination of 65 degrees, and a declination of -25 degrees. For these moderate to high susceptibility values, the effect on total magnetization is that the inclination decreases, and declination starts to rotate away from the inducing field in a clockwise direction (towards the long axis of the body). The magnetic response on the surface, as described in the previous section and illustrated in Figure 1, is that the data likewise rotate in similar clockwise fashion.

Table 1: Comparison of true and estimated magnetization directions for varying susceptibilities. Note that the estimation methods performed poorly for the tabular shaped body in Figure 1 with high magnetic susceptibility.

Susce	Inclination			Declination		
	True	Helbig	CrosCor	True	Helbig	CrosCor
1.0	56.9	46.6	43.0	-5.7	0.2	-57.0
3.0	45.7	34.8	44.0	6.05	8.7	-47.0
10.0	32.0	22.0	43.0	12.68	13.9	-32.0

In addition to the true magnetization direction, Table 1 presents results of direction estimates based on Helbig’s method and Cross-Correlation method. The algorithms were each implemented and recovered satisfactory estimates for a compact dipping body with remnant magnetization and low susceptibility (Dannemiller and Li, 2006). For our self-demagnetization problem, however, the methods did not perform very well. This is partly due to the increased complexity of the tabular shaped body which contains a significantly larger aspect ratio in both strike and dip relative to thickness. It is worth noting that Helbig’s method does adequately estimate declination for high susceptibility values, when self-demagnetization is present. However, neither method reliably recovers inclination for any of the susceptibility values.

Results of the estimation methods indicate that they may perform with significantly different results under the influence of strong self-demagnetization than that of remnant magnetization. Whether this is due solely to the differences in magnetic susceptibility, or also from geometry and orientation of the source body has yet to be studied.

Magnetization based inversion: The first inversion results presented are recovered by supplying total magnetization direction to an inversion algorithm as described by Dannemiller and Li (2006). Due to the variable range of estimated directional values and their poor approximation to true magnetization, we opt to supply the true magnetization direction to the inversion algorithm here for each susceptibility and analyze the performance of the approach under ideal conditions.

The first column of Figure 3 shows results of magnetization inversion for data which are moderately and strongly affected by self-demagnetization, respectively, as magnetic susceptibility is increased to (a) $\kappa = 1.0$ SI, and (b) $\kappa = 10.0$ SI. Results indicate that magnetization based inversion does not perform well in the presence of strong self-demagnetization, i.e. high magnetic susceptibilities, even when knowledge of true total magnetization direction is available.

Amplitude based inversion: The final inversion results, presented in the second column of Figure 3, are recovered by calculating the amplitude data of the same anomalous magnetic fields at high magnetic susceptibilities, $\kappa = 1.0$ SI and $\kappa = 10.0$ SI. The algorithm treats the amplitude data as the input data, and then recovers the distribution of magnetization as a function of 3D position in the subsurface. To illustrate the effectiveness of the method in the presence of strong self-demagnetization, results are presented in Figure 3 alongside those of the equivalent solution from magnetization based inversion. Figure 3(a,b) illustrates a comparative result of the two methods for $\kappa = 1.0$ SI, and (c,d) for $\kappa = 10.0$ SI. The datasets which were inverted are from moderate and high susceptible tabular bodies, respectively, and are each affected by self-demagnetization. Amplitude based inversion clearly performs better under the influence of self-demagnetization at high magnetic susceptibility than the magnetization based inversion. The former method constructs a smooth, compact body which adequately approximates dip of the original tabular structure. The later tends to produce solutions with rough structure, poor spatial resolution, and little indication of dip. A similar observation has likewise been observed by Lelièvre and Oldenburg (2006) in which the authors provide

an additional method of inverting for high susceptibility using full solution to Maxwell's equations. We note that neither method implemented here recovers the entire tabular model as it extends to depth. However, only amplitude inversion generates results which resemble the true dipping structure and make geologic sense for high susceptibilities.

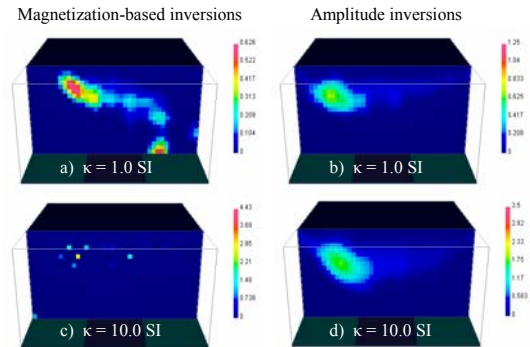


Figure 3: Comparison of Magnetization based inversion (left column) and Amplitude inversion (right column) for medium and high susceptibilities (top and bottom rows, respectively). Amplitude inversion clearly outperforms magnetization inversion when strong self-demagnetization is present at higher susceptibilities.

CONCLUSIONS

It is commonly accepted that adequate knowledge of true magnetization direction of a causative body is crucial in order to accurately interpret magnetic data by subsequent quantitative methods. Such assumption has been the driving force for development of many well recognized approaches for estimating total magnetization when strong remanence or self-demagnetization are present. Examples to which these methods are commonly applied include the interpretation of magnetic data over ferrous unexploded ordnance, banded iron formations, nickel deposits, kimberlite pipes, and depth to basement problems. This research has raised the question as to whether such a two-pronged approach for magnetic interpretation is appropriate in strongly magnetic environments. Numerical experiments demonstrate that directly inverting amplitude data (Shearer and Li, 2004), calculated from magnetic data yet weakly dependent on magnetization direction, may be better suited for self-demagnetization problems where one is dealing with high magnetic susceptibilities.

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