Application of magnetic amplitude inversion in exploration for natural gas in volcanics
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SUMMARY

We present a case study on the use of magnetic amplitude inversion in imaging volcanics that are buried in sedimentary basins and have strong remanent magnetization. The application arises in exploration of natural gas hosted in volcanic units. We show that combined with reliable approaches for magnetic anomaly separation, amplitude inversion can overcome the lack of information on magnetization direction and effectively identify the volcanic units at large depths.

INTRODUCTION

Exploration for natural gas hosted in volcanics in sedimentary basins often makes use of magnetic method because of difficulties associated with seismic imaging under such conditions. However, the interpretation of magnetic data in such applications can be hampered severely by the small amplitude of anomalies and the presence of remanent magnetization. In such cases, the remanent magnetization causes the total magnetization to be rotated to an unknown direction. As a result, inversions of the total-field anomaly are no longer useful because the magnetization direction is a piece of basic information required for such algorithms. Yet, inversion-based interpretation is often necessary given the weak anomalies from volcanics.

The magnetic amplitude inversion technique developed for mineral exploration (Shearer, 2005; Li et al., 2010) may be used as a viable tool to tackle this problem. This method inverts the amplitude of the magnetic anomaly vector, which is weakly dependent upon the source magnetization direction, and recovers a 3D distribution of magnitude of magnetization. We present a case study and show that such an approach is viable in exploration for natural gas hosted in volcanic units. However, it is important to be able to first extract the desired anomaly through a reliable separation technique.

Figure 1 displays a set of total-field magnetic data over a sedimentary basin with buried volcanics. The ambient field at this location has an inclination of 62° and declination of −1°. The basement depth in the area ranges from 6000 to 8000 m and the volcanics are located at intermediate depths. There appear to be a number of magnetic anomalies surrounding a broad magnetic low in the southwest quadrant. Drillings indicate that most magnetic highs visible in the data map are localized magnetic units of relatively young ages. The regions of broad magnetic low near the center was not considered an area of interest. However, the only two wells that intersected volcanics are located precisely in that magnetic low. Drill logs and core sample measurements indicate that the volcanics unit is located at depths just below 2500 m, its average susceptibility is 0.0144 SI and the maximum strength of remanent magnetization is about 1.16 A/m.

The question arises as to whether the magnetic anomaly due to the volcanics unit is contained in the data shown in Figure 1. Furthermore, if the answer is yes, how do we extract the anomaly and how can it be interpreted to yield useful information about the volcanics?

![Figure 1: The observed total-field magnetic data over a sedimentary basin with buried volcanics. Two wells (white circles) intersected volcanics at a depth of 2500 m directly below the broad low in the center of the map. However, there are no anomalies apparent in the data that could indicate the presence of volcanics at the location.](image)

ANOMALY SEPARATION

A closer inspection suggests that the total-field magnetic anomaly in Figure 1 consists of several distinct scales. The most obvious positive anomalies are of higher frequencies and localized. The broad anomalies have wavelengths on the order of tens of kilometers and they are clearly related to the basement. What is missing is a visually identifiable anomaly that can explain the drillhole intersection. Given the recognition of features on different scales in the data, we have computed the radially averaged power spectrum to examine the overall depth distribution of the sources. We can then fit the power spectrum with three distinct ensembles (Spector and Grant, 1970) and a constant noise power by using the following parametric function of radial wavenumber \( \omega_r \):

\[
P(\omega_r) = A_1 e^{-2h_1 \omega_r} + A_2 \omega_r^2 e^{-2h_2 \omega_r} + A_3 \omega_r^2 e^{-2h_3 \omega_r} + P_n
\]  

(1)

where \( A_i \) are the ensemble strengths, \( h_i \) the ensemble depths, and \( P_n \) the noise power. The first ensemble represents depth unlimited sources and the second and third are depth limited. The depths obtained from the least-squares fitting (top of Figure 2) are respectively 6000 m, 2800m, and 900 m. These are reasonable depths given the expected basement depth and the well intersection depth of volcanics. For comparison, the individual power spectra of the three ensembles are displayed in the lower panel of Figure 2.

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With the clear identification of different source depths, it is logical to carry out an anomaly separation by using a Wiener filter (Pawłowski and Hansen, 1990) to extract the anomaly corresponding to the second ensemble, which is interpreted as the volcanics. We use the derived ensemble power spectrum to represent the signal power to define the Wiener filter transfer function,

\[ Y(\omega) = \frac{A_2 \omega^2 e^{-2b_2 \omega}}{P(\omega)} \]  

The resultant anomaly data are shown in Figure 3. We have extracted a subset around the two wells. A set of well defined anomalies are clearly visible. However, the anomalies have a much stronger trough than expected at this high magnetic latitude (62°). This may indicate the presence of remanent magnetization and is consistent with the well log and core sample measurements. Based on this observation, we proceed with the interpretation of extracted anomaly data using the amplitude inversion.

Figure 2: Radially averaged power spectrum of the magnetic data in Figure 1 and its theoretical fit with three ensembles and noise (top). The three ensembles appear to represent magnetic sources at different distinct depths based on their power spectra (bottom).

**AMPLITUDE INVERSION**

**Algorithm**

The main impediment to the quantitative interpretation of magnetic data affected by remanent magnetization is the unknown magnetization direction. For isolated anomalies, one could either estimate the direction directly from data (Phillips, 2005; Lourenco and Morrison, 1973), or invert for the geometry as well as the magnetization of the source body (Taylor and Frawley, 1987). For more complex data sets with multiple anomalies, it is often necessary to take an alternative approach and work with the amplitude data that quantify the strength of the anomaly vector (Shearer, 2005; Li et al., 2010). The amplitude of the anomalous field vector is independent of the magnetization direction in 2D problems (Nabighian, 1972). This property stems from the fact that the amplitude of the magnetic anomaly vector is the envelope of each component of the vector. This property does not extend exactly to 3D problems, but the amplitude data are still only weakly dependent on magnetization direction. This approximate property enables us to examine remanently magnetized data directly and provides the opportunity for direct inversion for the strength of the source magnetization vector without the need for direction information.

The amplitude of the anomalous field vector, \( A \), is defined as

\[ A = |\vec{B}_a| = \sqrt{B_{ax}^2 + B_{ay}^2 + B_{az}^2} \]  

where \( B_{ax} \), \( B_{ay} \), and \( B_{az} \) are the three components of the magnetic anomaly. We calculate these different components in the Fourier domain. Figure 4 displays the amplitude data derived from the total-field anomaly shown in Figure 3. It is interesting to note the two intersecting wells are located along a northwest extension of the main amplitude anomaly in the center of the map. This is the first instance in this sequence of processing steps that produced an anomaly map with tangible correlation between a visible magnetic anomaly and a known unit of volcanics.

Figure 3: Subset of the total-field magnetic anomaly obtained from the Wiener filter. The two intersecting wells are located in the areas of negative magnetic anomaly. The strong negative peaks indicate the present of remanent magnetization.

To invert these data and construct a 3D model of the magnetization strength, we use a rather standard algorithm that minimizes an \( l_2 \) model objective function of the effective susceptibility subject to fitting the amplitude data. The effective susceptibility is defined as the ratio of the total magnetization strength over the current inducing field, \( B_0 \). The details can be found in Shearer (2005). The important components of the algorithm include a depth weighting function and positivity constraint that are applied to ensure a geologically interpretable model construction. Given the definition of amplitude
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Figure 4: Magnetic amplitude data calculated from the subset of the total field anomaly shown in Figure 3.

data in equation 3, the amplitude data are nonlinearly related to the effective susceptibility. Thus, we have a nonlinear inverse problem and we obtain its solution iteratively. Several positive results have been obtained in mineral exploration from the algorithm when applied to magnetic data affected by strong remanent magnetization. It is therefore natural to extend the algorithm to data sets in oil and gas exploration affected by remanent magnetization, such as the residual data in this presentation.

Results

To apply the above algorithm, we have defined a model region below the extracted data in Figure 4 with dimensions of 35 km by 35 km in east and north directions and extending to a depth of 7 km. This region is discretized into rectangular cells of 500 m by 500 m by 250 m in east, north, and depth direction. Beyond this core mesh, we have also extended the model region outwards horizontally and at depth by 7 km using cells with increasing sizes. The horizontal cell size of 500-m is chosen to be consistent with the processed amplitude data that has a grid spacing of 500 m. Spectral analysis of the original data show that this data spacing is small enough to capture all the frequency content in the data. Working at this discretization interval ensures that we have an easily manageable problem size for the 3D inversion while not aliasing the data through coarse sampling.

Figure 5 displays a volume rendered image of the recovered effective susceptibility model. The recovered maximum value is 0.03 SI, which is consistent with the fact that the intersected volcanics has a measured susceptibility of 0.014 and remanent magnetization of 1.15 A/m. The cutoff value is 0.01 so that only the susceptibility above this threshold is displayed. This threshold is chosen to be slightly lower than the measured susceptibility from the core samples.

The recovered model images a set of magnetic units and they are located at the expected depth range. The northwest extension of the main source body in the middle coincides with the volcanics intersected by the two wells. Thus, it is reasonable to infer that the amplitude inversion of the extracted residual data has produced a 3D image of the effective magnetic susceptibility correlating with the known volcanics.

CONCLUSION

We have applied a magnetic amplitude inversion algorithm developed for mineral exploration problems to a set of data acquired in exploration of natural gas hosted in volcanics in a sedimentary basin. The amplitude data were calculated from an anomaly that was extracted through a Wiener filter based ensemble-fitting of the radial power spectrum of the original data. The inverted effective susceptibility has successful delineating the volcanics unit encountered by the intersecting wells, which is the exploration target in this case.

This case study demonstrated the efficacy of combining anomaly separation techniques with amplitude inversion. The success of amplitude inversion in such applications will depend critically on the ability of extract anomalies due to the target source body. The Wiener filter based on ensemble power spectra worked reasonably well in this case, because the three units are well separated in depth. This is a rather ideal scenario. As is well known, one will encounter difficulties with this Wiener filter when sources are distributed closely in depth. Therefore, more robust anomaly separation techniques must be developed for interpreting magnetic data affected by strong remanent magnetization.

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Figure 5: Isosurface at 0.01 SI of the effective susceptibility model recovered from the magnetic amplitude inversion. A set of magnetic units are imaged and they are located at the correct depth range. The northwest extension of the main susceptibility zone should be the volcanics intersected by the two well shown as vertical blue lines.
EDITED REFERENCES
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