

Amplitude effects of magnetic signals on depth estimation routines

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ABSTRACT

Increased acquisition of geophysical data in conjunction with limited geological information places greater importance on accurate geophysical processing and interpretation methodologies. There are numerous semi-automated data processing routines presently being implemented which specialize in location, geometry, and depth of potential source bodies. Most routines rely on the innate relationship that magnetic signal frequency is a function of a magnetic source's depth and geometry. An additional relationship that is often not addressed is amplitude, which is a function of a source's magnetization. Most analytic routines incorporate some sort of mathematical entity in their fundamental equations to address magnetization effects. However, there are associated limitations of these analytic routines that must be clearly defined to accurately interpret the calculated results. The mathematical expression of tilt-angle has recently been developed into a depth-estimation routine, known as "tilt-depth". It has been shown to work reliably on sources that generate non-complex anomalies, which include a non-dipping body under the influence of a vertical magnetic field vector. It is important to consider how depth estimations will be effected when the amplitude of the source magnetization varies. Tilt-depth solutions become more inaccurate once the source approaches the surface and increases in magnetization. This is due to the creation of more complex signal geometry and reiterates the premise that the limitations of any of depth estimation routines must be considered and mitigated.

Key words: Magnetics, depth estimations

INTRODUCTION

With an increased rate at which magnetic data is acquired, more efficient semi-automatic processing routines have been developed. These analytic routines are designed to aid in the delineation of source body location, geometry, depth, and physical properties (i.e. magnetic susceptibility). Accordingly, analytic routines consist of depth estimators, which include but are not limited to iSPITM, analytic signal, Euler deconvolution and tilt-depth (Thurston and Smith, 1997; Smith *et al.*, 1998; Keating and Pilkington, 2004; Reid *et al.*, 1990; Salem *et al.*, 2007a; Salem *et al.*, 2008).

Tilt-depth is a recently developed methodology derived from tilt-angle and has shown reliable results for non-dipping, parallelepiped sources in a vertical ambient field (either occurring at the pole or having been properly reduced to the magnetic pole, RTP).

Tilt-angle was first introduced by Miller and Singh (1994) and has since been defined as:

$$\theta = \tan^{-1} \left(\frac{\partial M / \partial z}{\partial M / \partial h} \right) \quad (2)$$

$$\text{where } \frac{\partial M}{\partial h} = \sqrt{\left(\frac{\partial M}{\partial x} \right)^2 + \left(\frac{\partial M}{\partial y} \right)^2} \quad (3)$$

$$\text{and } \frac{\partial M}{\partial x}, \frac{\partial M}{\partial y}, \frac{\partial M}{\partial z} \quad (4)$$

are first-order derivatives of the magnetic field (M) in the directions of x, y, and z.

Since tilt-angle is an inverse trigonometric function all resultant values are between -90° and $+90^\circ$, therefore it normalizes all amplitudes to this range. Miller and Singh (1994) showed that tilt-angle was capable of edge detection and delineation of source body orientation. Tilt-angle will produce a zero value over or near the source edges with positive values over the source and negative values outside the source. This is similar to results produced by vertical derivatives, however unlike vertical derivatives tilt-angle is insensitive to source depth and can equally resolve deep and shallow sources.

Salem *et al.* (2007, 2008) introduced the concept that tilt-angle could be used as a simple method to delineate the depth to top of a source, known as “tilt-depth” method. Salem *et al.* (2007, 2008) extended the tilt-angle expression to derive a relationship between the horizontal location of a contact (h) and the depth to top of source (z_T):

$$\theta = \tan^{-1} \left(\frac{h}{z_T} \right) \quad (5)$$

This method calculates the depth to top by measuring the physical distance between tilt-angle pairs, with particular emphasis on the locus of the complementary 0° and $\pm 45^\circ$ pairs. When the results of tilt-angle are calculated and contoured, it is shown that the physical distance between -45° and $+45^\circ$ ($2h$) is equivalent to twice the depth to top ($2z_T$). This physical distance remains the same irrespective of magnetic susceptibility due to an integrated vertical and total horizontal gradients ratio (Equation 2).

However, what is the influence on depth estimates when they are calculated at different parts of the magnetic signal (non 0° and $\pm 45^\circ$) and therefore different amplitudes? Applying tilt-depth to two sources of differing magnetic susceptibility (and therefore of different amplitude) but at identical depths, it is shown that under specific circumstances depth estimation results such as those from tilt-depth become more complicated. It emphasizes that these complications need to be strongly considered when completing any sort of interpretation through the application of a pre-processing routine, such as filtering.

METHOD AND RESULTS

Deep source model (150m)

To compare the effect of different amplitudes, at a constant wavelength, we need to generate two comparable models with the same frequency content, but different amplitude. This is accomplished by varying the magnetization of the associated source. For simplicity we do this through changes in magnetic susceptibility, although it could also be achieved through variations in the Natural Remanent Magnetization (NRM). Two vertical-sided prisms of

identical geometry (length 400m, width 400m, thickness 40m) are generated and placed at a depth of 150m below surface in a perfectly vertical ambient field of 60 000nT. This avoids having to apply RTP. The sensor is treated to be at ground surface. The only difference between the two sources is that one has a magnetic susceptibility of 0.001SI (Source A) and the other a susceptibility of 1.4SI (Source B). This allows for three orders of magnitude difference in magnetization of the two sources. A profile of source location and resultant total magnetic intensity (TMI) anomaly can be seen in Figure 1.

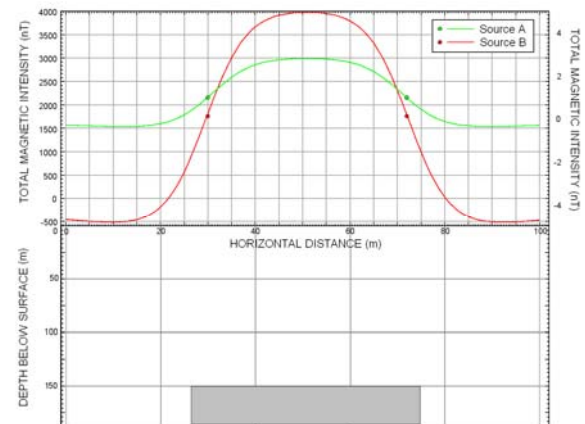


Figure 1. TMI anomalies generated by two sources of identical geometry but different magnetic susceptibilities, both at a depth of 150m. Points of inflection (•) indicate source edges. Magnetic intensity for Source A and Source B are shown along the right and left vertical axes respectively, as they are at different scales to emphasize signal geometry.

Tilt-angle is calculated from the associated TMI data for each source. Contour locations are calculated for every 5° increment of tilt-angle (i.e. 5° , 10° , 15° , ...). The computed tilt-depths based on Equation 5 can be seen in Figure 2. Source A has a tilt-depth average of $68.97\text{m} \pm 14.21$ and Source B has a tilt-depth average of $66.55\text{m} \pm 13.61$ for a total difference of $2.42\text{m} \pm 0.43$. Tilt-depth in this case has not provided the correct depth (150m) due to an orientation parameter (magnetic field declination relative to the source edge). For the interest of this article, the primary objective is whether the calculated depths significantly change with differing magnetization and not whether the calculated depths are accurate. This being said, the depth estimates under these conditions will be the same regardless of the source's magnetization.

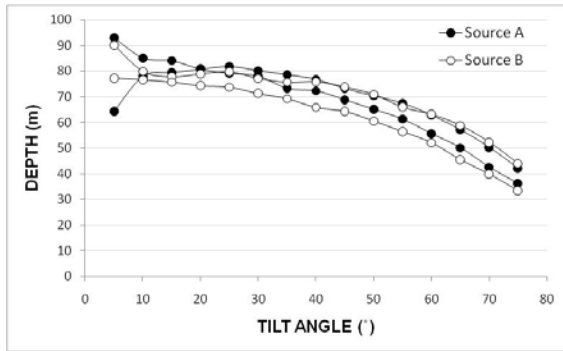


Figure 2. Tilt-depth results for source A and B. Computation of z_T for all negative tilt-angle contours results in negative depths. Therefore the absolute value has been taken for all depths and negative tilt-angles (shown on a positive scale). The calculated depths for both data sets are near identical in both trend and values. The trend exhibits a declining depth value (more shallow) with increased tilt-angle. For the sake of this paper, the trend has been disregarded for the time being as it is identical in both data sets and does not affect the comparison between the two.

Shallow source model (50m)

Typically, the closer a source is to surface, the more reliable the results. One would expect a smaller difference between the calculated tilt-depths when the sources are located closer to surface. In this case, the same sources used in the deep model are placed at a depth of 50m below surface. Once again the ambient field is perfectly vertical to avoid RTP. The TMI is calculated over the sources (Figure 3), from which tilt-angle is determined.

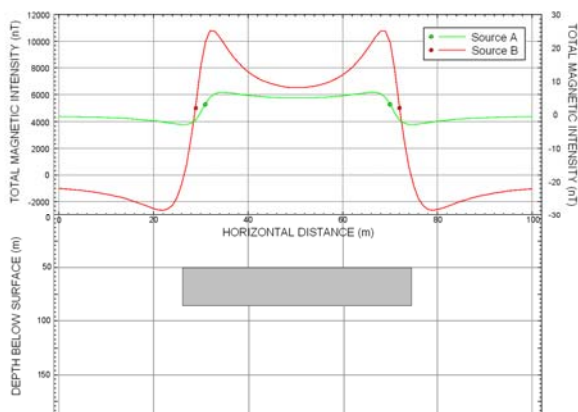


Figure 3. TMI anomaly generated by two identical sources at 50m depth. Points of inflection (•) indicate source edges. A 2m difference between the points of inflection locations in both data sets is noted. This difference is a precursor to signal effects on calculated tilt-depths. Magnetic intensity for Source A and B are shown along the right and left vertical axes respectively, as they are at different scales to emphasize signal geometry.

The results for calculated tilt-depth for every 5th tilt angle can be seen in Figure 4. Source A has a tilt-depth average of 50.11m ± 8.84 and Source B has an average tilt-depth of 30.06m ± 4.16. This accounts for a difference of 20.04m ± 0.43. This difference is one order of magnitude greater than the difference seen in the deep source model. This suggests that tilt-depth does not work as effectively for near-surface sources.

Typically, the geometry of magnetic signal is dominated by the depth to top and minimally by the depth to bottom (Spector and Grant, 1970). Since a magnetic field will decay at a rate inversely proportional to source-signal distance cubed, often the signal generated by the bottom of the source has decayed before reaching the sensor. This is true for most cases and as such the depth to bottom is typically not taken into consideration. In isolated instances, such as with very thin, shallow bodies, the depth to bottom does have a significant influence on the resultant anomaly. In this situation, the signal produced by the bottom of the source is readily detectable by the sensor.

Since the TMI signal at any point represents the summation of all sources within proximity. The ridges and troughs (anomalies) which characterize all TMI maps are a record of the summation (interference) of the field generated by various sources. Applying an analytic routine to this type of mixed source data will produce many solutions that are not geologically meaningful. This emphasizes the importance of the application of filtering routines prior to any sort of processing and interpretation.

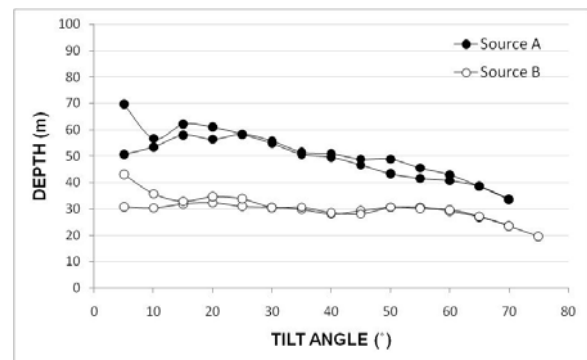


Figure 4. Tilt-depth results for source A and B. Computation of z_T for all negative tilt-angle contours results in negative depths. Therefore, the absolute value has been taken for all depths and negative tilt-angles. The calculated depths for both data sets are similar in trend but different in values. Once again both data sets exhibit a declining trend with increased tilt-angle. Since the trends are near identical in both data sets, they have been ignored.

CONCLUSIONS

Tilt-depth, along with almost all depth estimation routines work reliably under ideal conditions, which is typically a non-dipping source in a vertical ambient field. Furthermore, most depth-estimation routines incorporate some mathematical function into their fundamental equations (such as Equation 1 for tilt-depth) that allow for depth-estimations to be identical regardless of source magnetization (and thus amplitude). This was shown through a specific example where tilt-depth is applied to a synthetically generated model at a depth of 150m.

That being said, depth-estimations do not work under all conditions. The reason why tilt-depth fails for shallow sources is that like most semi-automatic interpretation routines, it involves gradients of the magnetic field, with the primary assumption that the data within an individual window defines a single isolated magnetic anomaly associated with a single geological source. However these conditions are rarely met. In this case, although there is a single geological source, a mixed magnetic signal was generated due to the interaction between the signal generated by the source depth and that of the source bottom. This denotes why processing routine limitations need to be considered.

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