On the use of different methods for estimating magnetic depth

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Magnetic depth estimation plays an important role in magnetic interpretation. A complete quantitative interpretation of potential fields data aims to estimate three types of information about sources of geologic interest: the depth, the dimension, and the contrast in the relevant physical property. Such an interpretation suffers from inherent ambiguity. It is impossible to obtain all three types of information simultaneously without other a priori information. In many applications, we are often interested in depth more than either dimension or physical property contrast. Thus, different quick methods have been developed, over half a century, to estimate the magnetic depth. These methods work for simplified source geometries (dimensions) and are independent of the susceptibility contrast. The depths estimated by some method can be used as the final, quantitative solution in some ideal situations—i.e., the anomaly is well isolated and the noise is insignificant or well removed. It is more often that estimated depths provide a good starting point for a genuine structural interpretation (e.g., an interactive modeling or a constrained inversion).

In petroleum exploration, for example, the structural surface interpreted from magnetic depth estimates is often the best available approximation to the true crystalline (i.e., metamorphic/igneous) basement configuration. Basement depth (or equivalently, sedimentary thickness) is a primary exploration risk parameter. Estimates of basement depth are directly applicable to basin modeling (e.g., source rock volume estimation) and thermal maturity applications (e.g., source-rock burial-depth). Basement structure inferred from magnetic depth estimates provides insight into the evolution of more recent sedimentary features (e.g., sub/minibasin compartmentalization, salt structure distribution/kinesis, localization of reservoir-bearing structures) in areas where the inherited basement fabric/architecture has affected (either continuously or episodically) basin evolution and development. Examples of the latter are the prolific, passive rifted margins of the southern Atlantic Ocean. A basin's "plumbing" often exploits faults and fractures within the sedimentary section that are of basement origin. The movement and flow of fluids within a basin, such as hydrocarbon migration along lateral and vertical carrier beds, can be facilitated by basement-involved sedimentary faults/fractures. Basin heat-flow patterns can also be moderated by fluid circulation along basement-involved fault systems. Thus the ability to estimate/interpret basement structure via magnetic depth estimates provides a more complete understanding of critical first-order basin exploration parameters. Within the last decade, magnetic depth estimates have also been widely applied for the mapping of sedimentary faults, folds, channels, and salt structures. This more recent application results from major advances in magnetic surveying (primarily GPS navigation) and interpretation technologies.

There are many depth estimation methods. The number keeps growing with continual development of new algorithms. These methods include: slope, Naudy, Werner deconvolution, analytical signal, Euler deconvolution, Euler deconvolution of the analytical signal, source parameter imaging (SPI or local wavenumber), the continuous wavelet transform (CWT). The Peters half-slope is a manual method developed 50 years ago, and its variants include the straight-slope and the Bean ratio. The others are all often categorized as automatic methods. SPI and CWT were developed only in the last six years.

Table 1. *A summary of the use of the moving window concept by different methods*

Method	Use of moving window
Naudy	Yes
Werner deconvolution	Yes
Euler deconvolution	Yes
SPI	No
CWT	No

Table 2. *Different methods work for only certain idealized sources. All the sources have an integer SI: 0 for contact, 1 for thin dike, 2 for horizontal or vertical cylinder and thin-bed fault, and 3 for sphere while linking to Euler deconvolution of the magnetic field*

	Contact	Thin dike	Horizontal cylinder	Vertical cylinder	Sphere
Naudy	Yes	Yes	No	No	No
Werner	Yes	Yes	No	No	No
Euler	Yes	Yes	Yes	Yes	Yes
SPI	Yes	Yes	Yes	No	No
CWT	Yes	Yes	Yes	Yes	Yes

Table 3. *Different methods require different derivatives. The original Naudy method doesn't require any derivatives, and some versions may work on the first-order vertical derivative of the TMI anomaly. Werner deconvolution works on the TMI for a thin dike model, and on the horizontal derivative of the TMI for a contact. The standard Euler deconvolution method (of the magnetic field) uses the first-order derivatives only, and Euler deconvolution can also be applied to a derivative or a combination of derivatives in which second- or even higher-order derivatives may be required. The SPI method requires second-order derivatives and iSPI third-order ones. In the CWT method, the nth-order wavelet transform coefficients are calculated from the analytical signal amplitude of the (n-1)th order vertical derivative of the TMI. In general, the first-order coefficients are used and the first-order derivatives of the TMI are thus required*

	Horizontal derivative	Vertical derivative	Higher-order derivative
Naudy	No	optional	No
Werner	Yes	No	No
Euler	Yes	Yes	optional
SPI	Yes	Yes	Yes
CWT	Yes	Yes	optional

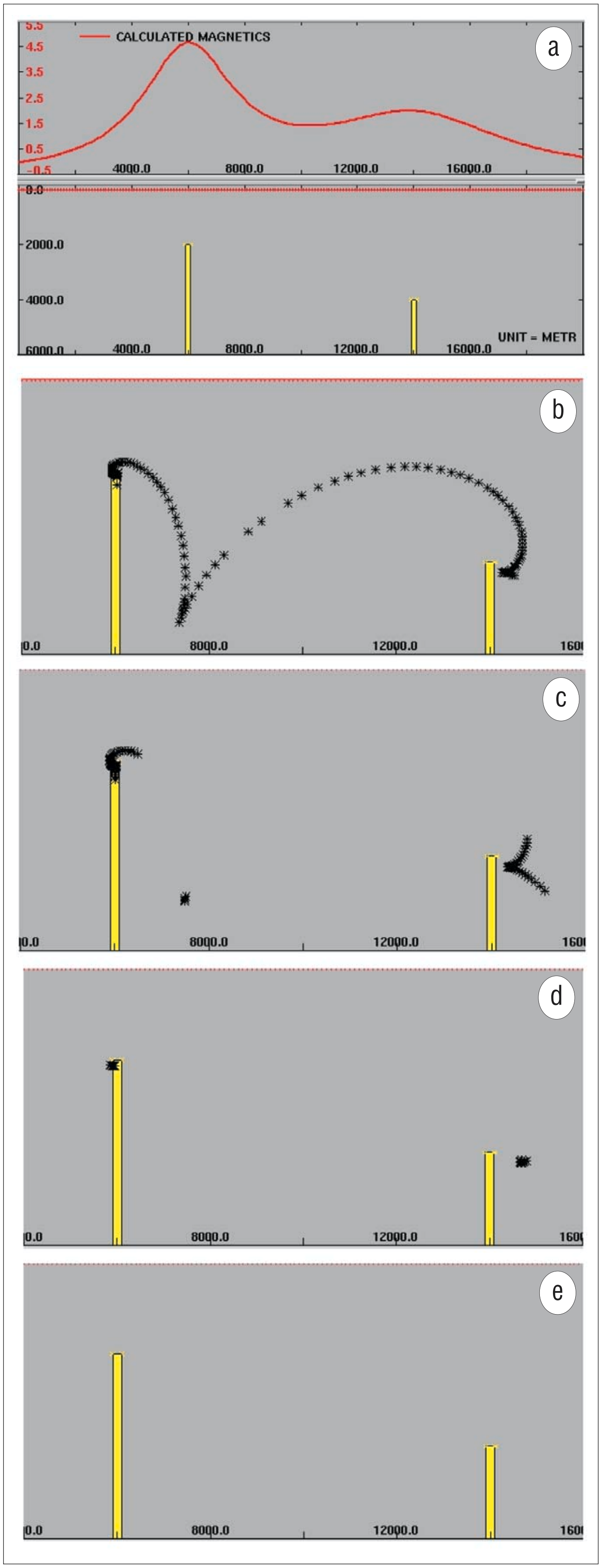

Figure 1. A synthetic model demonstrates the effects of the moving window. (a) The TMI responses produced by a two vertical dike model (lower panel) with a vertical inclination. Euler deconvolution solutions for the moving window width of (b) 1000 m, (c) 2000 m, (d), 6000 m, and (e) 8000. For illustration purposes, solutions in (b)-(e) have been zoomed into a laterally smaller portion of the modeling area in the lower panel of (a).

However, no single method is best overall. In fact, there may never be an ultimate solution to the depth estimation problem. At present, personal preferences fill the void that rational selection criteria should occupy. Different persons or groups prefer different methods. To my knowledge, no guideline has been established for help in selecting a proper or optimal depth estimate method (or methods) from the many possible candidates, and hence deriving an accurate, reliable depth solution. This article proposes one suggestion (not to say guideline) and makes one recommendation. The suggestion is that a proper or optimal method should be selected according to the data quality and the nature of the particular geologic problem. The recommendation is that in practice, in order to produce an accurate depth solution, it is better to use more than one reasonable method, together with experience and other geologic and geophysical knowledge.

Different methods. The five depth estimate methods listed in Tables 1-3 can be briefly assessed as follows:

1) The Naudy method is a curve-matching technique. The estimate is done via a look-up table technique. The accuracy is closely associated with these tables.
2) The virtue of Werner deconvolution is its transformation of a complex, nonlinear magnetic inversion (for depth, dip, and susceptibility) into a simple linear inversion.
3) Euler deconvolution uses Euler's homogeneity equation to construct a system of linear equations and then solve it, in least-squares sense, for the single putative source of a given type. Since Euler's homogeneity equation holds not only for the magnetic field itself, but also for its derivative and a combination of derivatives, people have developed Euler deconvolution of the analytical signal or of the first- or second-order vertical derivative of the magnetic field so as to determine the structure index (SI) and/or to improve the resolution. Two advantages of Euler deconvolution over many other methods are perhaps its easy generalization from 2D (profile analysis) to 3D (grid analysis) and its capability of directly applying to observations with variable altitudes.
4) SPI is a complex analytical signal technique, using not only the magnitude of the analytical signal but also the phase.
5) Mathematically, CWT is just the upward continuation of the analytical signal amplitude multiplied by the continuation distance.

I explain next how, for one's particular case, to select a proper method. Tables 1-3 represent three aspects critical to a successful application of a method. Posed as questions, the three aspects are: Does the method use the moving-window concept? What types of source geometries can the method treat in theory? Does it require derivatives—and if so, just first-order derivatives only or second- or even third-order derivatives in addition? I believe that the analyses and conclusions in this article can be equally applied to other magnetic depth estimate methods, although only five are listed in the tables.

Table 1 summarizes the use of the moving-window concept by different techniques. All the earlier automatic techniques use a moving window. One might even say that it is the use of a moving window that makes magnetic depth estimation automatic. Previously estimation had been purely manual. In fact, "computer-assisted," instead of "automatic," was once used to label the newer methods, and is still a better definition. Notwithstanding their early successes, the moving window has some drawbacks, as discussed more

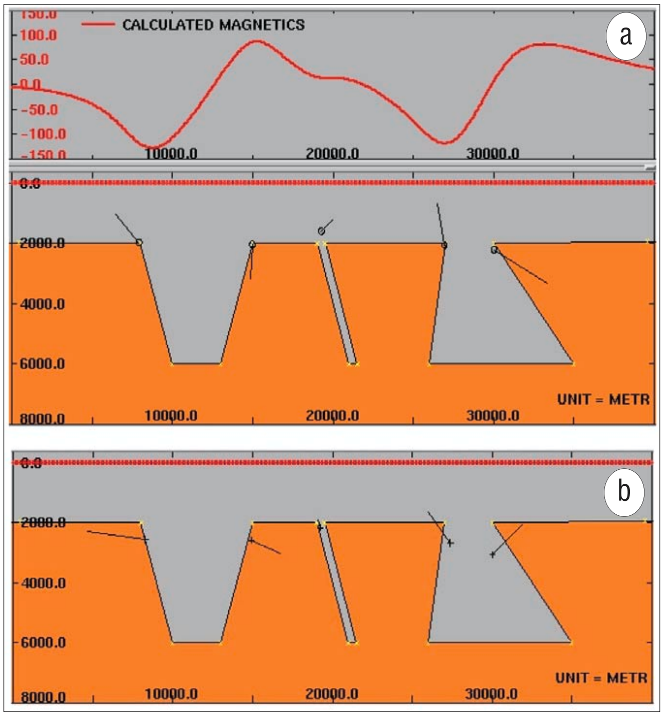

Figure 2. (a) TMI responses (upper panel) produced by a model with two grabens and one thin dike (lower panel). The magnetic field strength, inclination, declination, and profile azimuth are assumed to be 10 000 nT, 45°, 45°, and 90°, respectively. Circles on the model are Werner deconvolution depth solutions by assuming the contact model. (b) Crosses are Werner depth solutions for an assumption of the thin dike model. Lines start at circles or crosses. Their directions indicate the dipping angles and their lengths the susceptibility contrast for the contact and the susceptibility-thickness product for the thin dike. The moving window width used is 2000 m and the tolerance is tight (1%) since the synthetic TMI responses are noise-free.

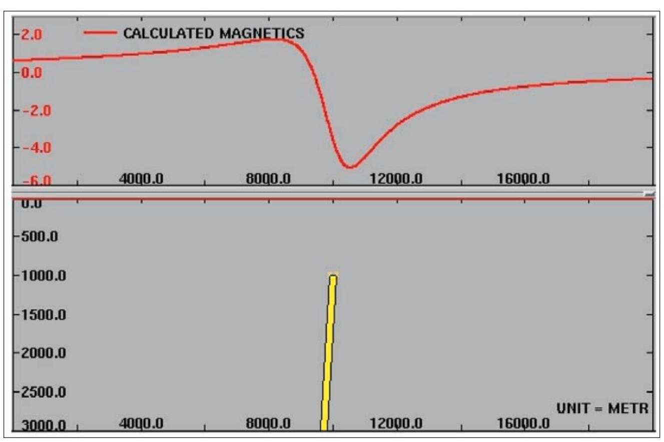

Figure 3. A single, dipping-dike model (lower panel) and its TMI responses. The magnetic field strength, inclination, and declination are assumed to be 20 000 nT, 30°, and 45°, respectively.

fully below. Some newer techniques such as SPI and CWT don't need the moving window.

Table 2 explains idealized sources assumed and used by different methods. To my knowledge, no single depth estimate method can work for an arbitrary geometry. All the methods work for idealized source geometries. Different methods work for different geometries. SI, a concept arising out of Euler deconvolution, is widely used to characterize the source geometry. It represents the fall-off rate or the negative of the degree of Euler's homogeneity. For the magnetic field, SIs are 0, 1, 2, and 3 for the contact, thin dike, horizontal (or vertical) cylinder, and sphere, respectively. Interestingly, SI for a thin-bed fault is 2, the same as a horizontal cylinder. This is because of the assumption that the thickness of the bed and the vertical throw of the fault are both much smaller than its burial depth. How does one make a proper selection? For example, to solve the kimberlite pipe problem, use Euler deconvolution or CWT, not Naudy nor Werner.

Many methods solve for depth while assuming geometry. However, some later methods can determine depth and geometry simultaneously. These methods may include Euler deconvolution of the analytical signal, iSPI (lowercase i stands for improved), and CWT.

The third and last table (Table 3) summarizes the use of derivatives by different methods. The original Naudy method doesn't use derivatives at all. Werner deconvolution uses the horizontal derivative when the source is a contact model. However, SPI and iSPI require second- and third-order derivatives, respectively. An accurate calculation of second- and third-order derivatives is often difficult when data contain noise. This leads to one easy rule regarding proper selection: If noise in data is strong, just select a method that doesn't use the derivatives or uses only the horizontal derivative.

Basically, the three aspects we have looked at represent three problems or three difficulties in practice. The first two difficulties, i.e., the moving window and the source geometry, largely suffer from interference and the third, the derivative calculation, from noise in data. In the following sections, I further analyze the difficulties, suggest possible ways to overcome or avoid each of them, and at last, propose a comprehensive approach to achieving an accurate depth solution.

Moving window. Figure 1a shows a synthetic model, consisting of two vertical thin dikes 8 km apart and its TMI (total magnetic intensity) responses. No noise has been added. Ideally, we expect only two individual point solutions at the top of each dike. Figures 1b-e display Euler deconvolution solutions for the moving window widths of 1000, 2000, 6000, and 8000 m, respectively. SI is given as 1, the correct value for a thin dike. Evidently, the solutions are not just two individual points. They are scattered unless the window width is too large. The scattering of solutions reduces with increasing the window size: from 1000 (Figure 1b) to 2000 (Figure 1c) to 6000 m (Figure 1d). When the window width has approximately a value of the distance between two anomalies, i.e., 8000 m, no single solution is obtained at all because the window is too wide (Figure 1e). In practice, sources are located at different depths and their resulting anomalies have different wavelengths. The interference obstructs a correct choice of the window width. The moving window will cause scattering if there is interference. Different methods treat interference differently. For example, Werner deconvolution takes it into account by introducing a polynomial background (in each window). However, in the standard Euler deconvolution method, we can only assume it to be constant.

How does one reduce scattering and obtain a tight cluster? In general, the following rule of thumb may be helpful: An optimum window size is small enough to see only a single anomaly yet large enough to cover sufficient variations in slopes or curvatures in the magnetic field. Many groups have been investigating some ways to obtain a tight cluster, such as statistical analysis, singularity analysis of the linear system, and extended Euler deconvolution. Those techniques do work well and are helpful.

There are three possible ways to overcome the moving window difficulty.

First, work on significant anomalies individually. This means that the method is no longer automatic. However, the solutions are often more reliable. This is particularly effective for checking the accuracy and reliability of an automatic method. For the two-dike model in Figure 1, we will get only two quite accurate depth solutions if we pick two anomalies near the two TMI maxima.

Second, use a method that doesn't require the moving window concept. Such techniques include SPI, iSPI, and CWT.

Third, develop and use a technique that allows multiple sources within a single window, such as multiple-source Werner or Euler deconvolution. Interference of neighboring sources is the major factor that causes scattering of solutions.

Source geometry. Figure 2 shows a synthetic model consisting of two grabens and one thin dike. When we assume a contact model and perform Werner deconvolution, we get accurate depth solutions for the grabens (contact corners) but not for the dike. When we assume a dike model, we get an accurate solution for the dike but not for the grabens. This suggests that the assumption or selection of geometry is critical.

How can we know the geometry correctly? There are two ways. First, know geometry from geology. All the older techniques, such as the Naudy method, Werner and Euler deconvolution, analytical signal, and SPI, either require or can utilize an assumption of source geometry. In practice, there are many different means to derive geometry from geology. In particular, the experience of an interpreter, familiar with magnetic responses from various geologic situations becomes invaluable. Some rules that may be helpful are:

- The anomalies frequently exhibit typical patterns that dictate the choice of the model. Linear features in the magnetic anomaly often correspond to dikes or faults, not vertical cylinders or spheres. If the basement is of interest, the contact, not the dike or cylinder should be used.
- Assume a thin dike source if there is a single TGR (the magnitude of the total gradient) maxima and two HGR (the magnitude of the horizontal gradient) maxima. Assume a contact if there is a single TGR maximum and a single HGR maximum.
- Above all else, the criterion of consistency should be widely applied. Geometric assumptions must be in reasonable agreement with adjacent lines.

Second, use automatic estimation of source geometry. Some methods (such as iSPI, Euler deconvolution of the analytical signal, and CWT) can determine depth and source geometry (indicated by the SI) simultaneously. iSPI requires the third-order derivatives of TMI, and Euler deconvolution of the analytical signal needs the second-order derivatives. CWT is largely an upward continuation of the analytical signal amplitude (i.e., requiring the first-order derivatives only).

For the automatic determination of SI, it is worth emphasizing the following two points. (1) This determination doesn't mean that the source geometry could be arbitrary. As explained earlier, all the different methods work for idealized bodies. Strictly speaking, the SI must be an integer. (2) It works well for an isolated anomaly caused by an isolated body. Interference, from other magnetic sources, complicates the interpretation. We take as an example the magnetic anomalies due to a deep vertical dike and a shallow horizontal cylinder, both having vertical magnetization. The central portions of the anomalies may be almost identical although their depths are very different. The key to distinguish them lies in the outer parts, where the cylinder develops a negative effect. However, this is exactly the part of the curve subject to interference from neighboring features. In practice, and from one profile alone, it is almost impossible to choose between a deep dike and a shallow cylinder.

For the synthetic, dipping-dike model in Figure 3, CWT is able to produce excellent solutions of both depth and SI.

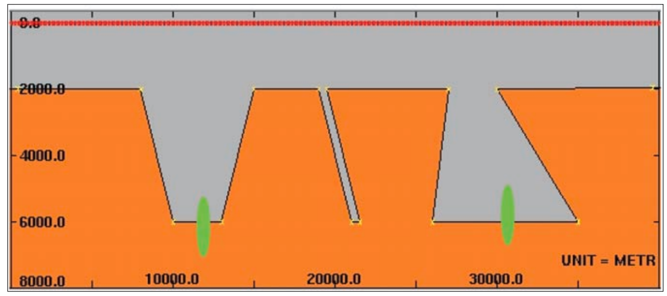

Figure 4. CWT applied to the complex model in Figure 2 produces two groups of poor solutions (green) and SI estimates ranging from 2.6 to 2.9.

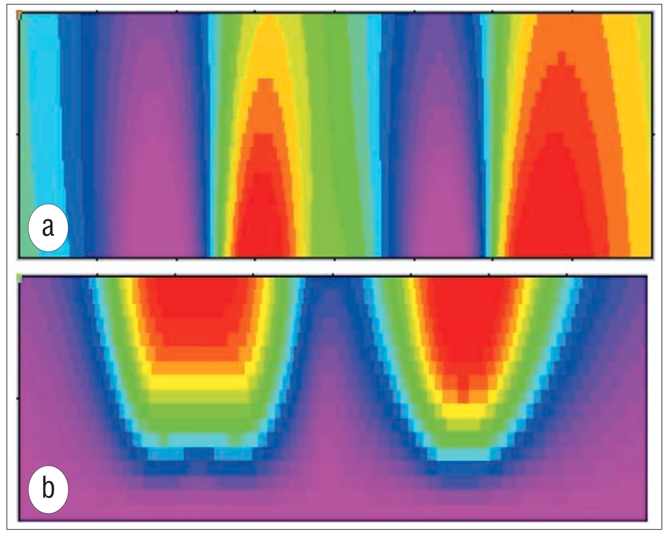

Figure 5. (a) Upward continuation results of TMI in Figure 2a. (b) The wavelet transform coefficients, calculated from the upward-continued analytical signal amplitude multiplied by the continuation distance. As indicated in Figure 2, the profile is 40 000 m long. There are 40 continuation levels and the largest continuation distance is 2000 m.

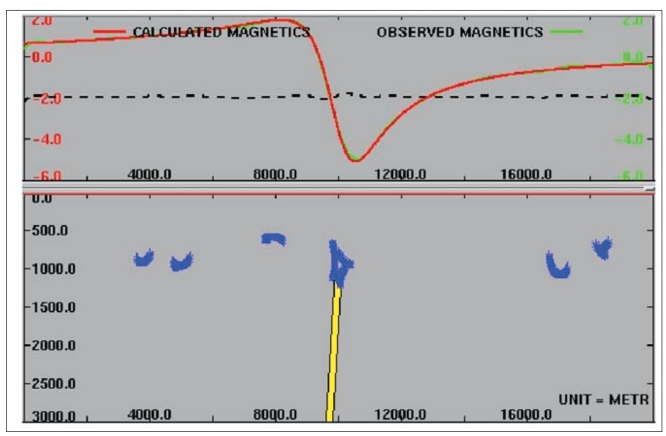

Figure 6. Scattering of Euler deconvolution solutions (blue) for the dipping dike model. A random Gaussian noise distribution is first added to the noise-free TMI responses. The Wiener filter is then used to remove noise. The black dashed line represents the difference between the denoised data ("observed magnetics") and noise-free TMI ("calculated magnetics"). Euler deconvolution is applied to the denoised data.

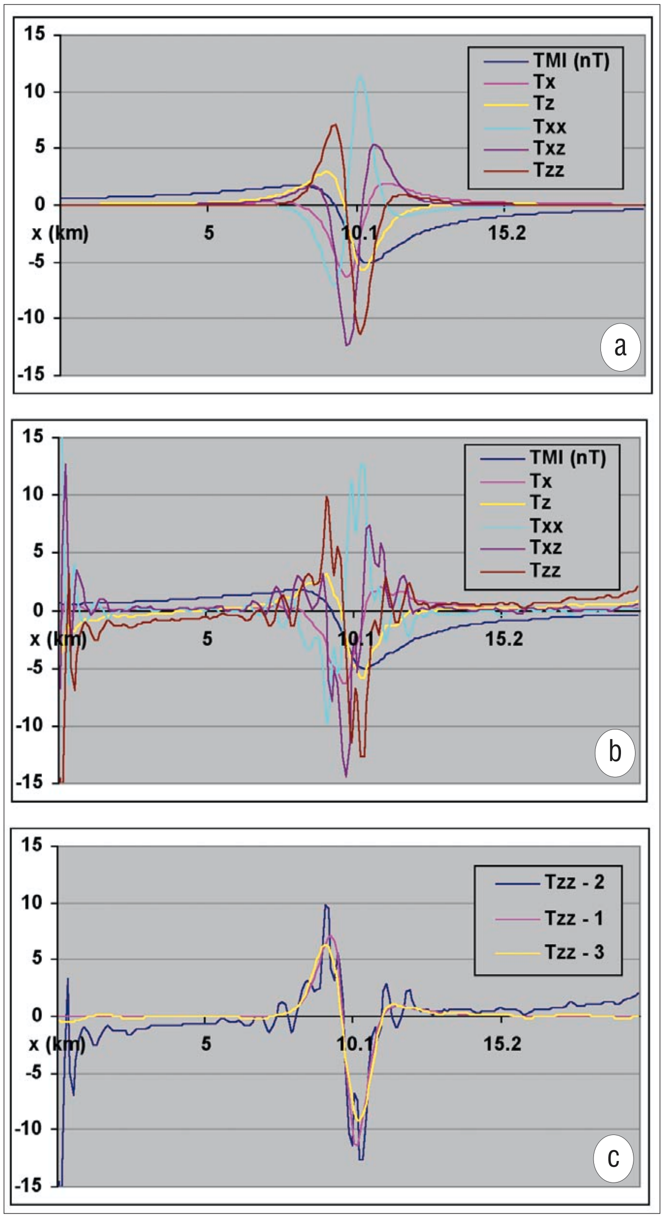

Figure 7. Effects of noise on the calculation of derivatives. (a) The noise-free TMI (the same as in Figure 3), and the first- and second-order derivatives calculated from the noise-free TMI. (b) The denoised TMI (the same as "observed magnetics" in Figure 6) and the first- and second-order derivatives calculated from the denoised TMI without an application of low-pass filter. (c) The second-order derivative Tzz calculated from the noise-free TMI (Tzz-1), denoised TMI (Tzz-2), and denoised and then low-pass filtered TMI (Tzz-3). Abscissa here is in km (it is m in Figures 3 and 6).

The true (x,z) is (10 000, 1000). The 34 solutions, derived from the total 40 continuation levels, produce x estimates ranging from 9980 to 10 000, z from 1030 to 1078, and SI from 1.0 to 1.1. However, the same method fails when it is applied to a complex model. Figure 4 displays CWT depth and SI estimates for the model in Figure 2. For exploration the solutions are unacceptable.

The poor resolution of CWT is clear in Figure 5. The wavelet transform coefficients are the upward continued analytical signal amplitude multiplied by the continuation distance. This depth estimate uses curves linking maxima at every continuation level. Unfortunately, the upward continuation of the analytical signal amplitude rapidly degrades the lateral resolution. Five anomalies visible in the TMI at the observation level become two in the wavelet transform coefficients. By the way, some working groups use CWT as an effective way to suppress the effects of noise on depth estimates. The advantage—insensitive to noise in data—and the disadvantage—poor lateral resolution—are both due to the same feature: the upward continuation of the analytical signal amplitude. Regardless, CWT is a powerful method; for an isolated body, it can simultaneously determine depth, source geometry, dip, and susceptibility from the first-order derivatives only.

Derivatives. How about the iSPI or Euler deconvolution of the analytical signal for determination of geometry if CWT doesn't work well? Unfortunately, these methods may have an even greater challenge—the calculation of higher-order derivatives. Derivatives are easy to calculate in theory, but difficult in practice. It is easy to calculate the derivatives used for qualitative interpretation such as the lineament analysis. In that case, we care only about the horizontal locations of derivative or gradient maxima or minima. However, it is difficult to calculate derivatives required by quantitative analyses such as depth interpretation. In this latter case, we need accurate locations and accurate magnitudes of the maxima or minima. Because of noise in data, it is difficult to calculate the magnitudes accurately.

For the single dipping dike model in Figure 3 and for the noise-free TMI responses, Euler deconvolution just like CWT can produce a tight cluster of accurate depth solutions. We now add random Gaussian noise to the TMI, and then apply different techniques including the wavelet denoising to remove the noise. Wiener filtering produces very good denoised results when the noise power is given correctly, 0.5 nT in this case. As seen in Figure 6, the maximum denoising error is smaller than 0.2 nT, compared to the peak-to-peak anomaly magnitude of about 7 nT. Even so, Euler deconvolution creates false solution clusters besides the true one.

Figure 7 depicts clearly the noise effects on the calculation of the first- and second-order derivatives, for the dipping dike model. Standard Euler deconvolution requires first-order derivatives only. The two first-order derivatives Tx and Tz used to generate the depth solutions in Figure 6 are calculated from the denoised TMI and can be found in Figure 7b. The noise effects on Tx and Tz are evident. These effects become severe in the second-order derivatives. I calculate the horizontal derivative by the finite difference, and the vertical derivative from the horizontal derivative via the Hilbert transform or the Laplace equation. This vertical derivative calculation is a relatively stable approach. In order to make the calculation more stable and the derivative results better, a further, popular solution is to apply a low-pass filter. Figure 7c compares the second-order derivative Tzz calculated from the noise-free TMI, the above denoised TMI, and the 1000-m low-pass filtered result of the denoised TMI. A proper low-pass filtering does improve the derivatives but still has difficulty to reconstruct their magnitudes accurately. An inaccurate magnitude will result in an inaccurate depth estimate. This is for a synthetic model test. The calculation becomes worse for the real data.

Beyond depth and 2D. Different working groups have extended different methods (Werner deconvolution, Euler deconvolution, SPI, and CWT) to determine dip and susceptibility besides depth. In fact, one can estimate the dip and susceptibility contrast only when the source location is known and the source geometry (e.g., SI) is known or correctly assumed. In the case of a contact, one can then solve for the dip and susceptibility contrast. For a thin dike, the

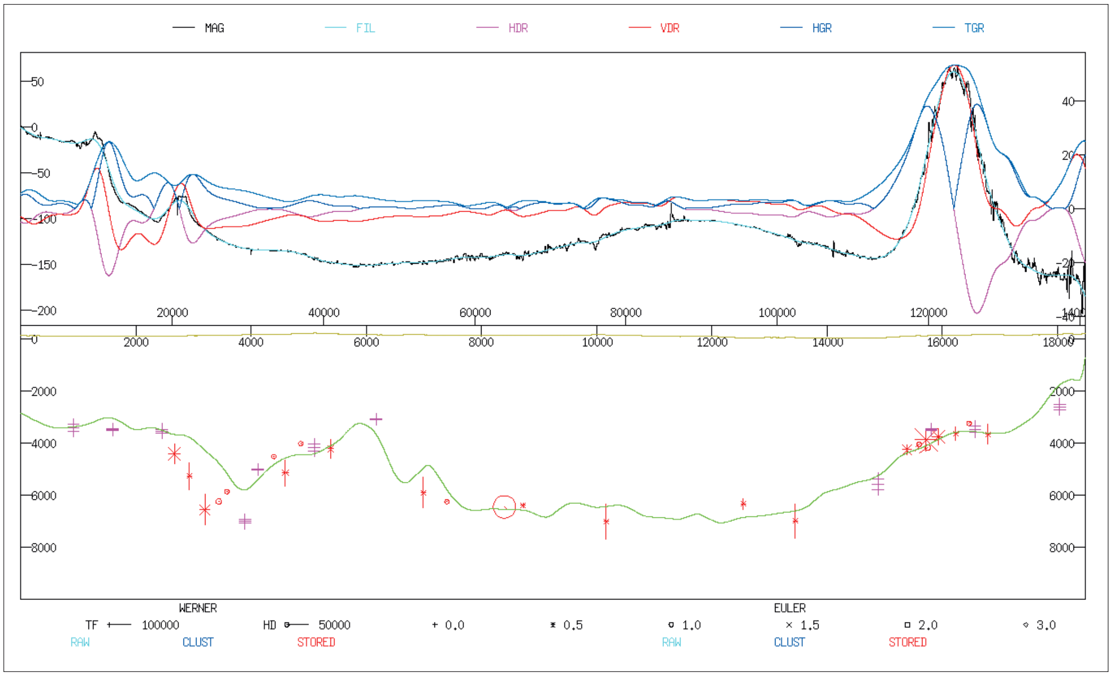

Figure 8. A real data profile (the raw TMI, filtered TMI, horizontal and vertical derivatives, horizontal and total gradients all shown in upper panel) and the final depth solution (green line in lower panel) derived by a comprehensive approach. The Bean ratio, Werner, and Euler deconvolution have been used. Depths have been picked, following the automatic clustering, manually by comparing to the TMI, derivative and gradient anomalies, and with a consideration of solutions on adjacent lines.

dip and the susceptibility-thickness product may be estimated. In the case of a horizontal cylinder, it is possible to determine the product of its cross-section area and the susceptibility. In general, the estimate of dip and susceptibility is less accurate than the depth estimate. Figure 2 shows the dip and susceptibility together with depth estimated by Werner deconvolution.

Depth estimation from gridded data (i.e., 3D analysis) may be not as accurate as estimation from field profile data (i.e., 2D analysis). One reason lies with the calculation of derivatives. In an airborne magnetic survey, the along-line data are densely sampled and the cross-line information poorly recovered. It is thus difficult to calculate accurately all needed derivatives. For example, in standard 3D Euler deconvolution, we need first-order derivatives along all three orthogonal directions but only one horizontal derivative may be accurately and reliably calculated. On the other hand, at a first glance, 3D analysis is more realistic because the real geology is 3D. All the methods can work for idealized sources in theory but only one of those sources, the sphere, is a real 3D body; the others have one or more infinite dimensions.

A comprehensive approach. Magnetic depth estimation is neither magnetic inversion nor a "black box." Magnetic inversion for structure (including depth) requires knowledge of susceptibility contrast and magnetization direction. Most importantly, an accurate inversion requires many constraints. The depth estimate methods work for simplified source geometries and are independent of the susceptibility contrast. The automatic methods are also independent of magnetization direction. They can often generate a quick (much quicker than magnetic inversion) interpretation of magnetic data. In practice, I strongly recommend a comprehensive and integrated approach to deriving an accurate depth solution. This approach involves the following essential aspects:

1) Select proper or optimal methods, e.g., per suggestions made in this article.
2) Apply more than one reasonable method to the same data set. For example, for a contact or thin dike problem with average noise in data, one may run the Naudy, Werner deconvolution, and Euler deconvolution, instead of just one method. Finding a common solution of different reasonable methods tends to increase the reliability of solutions.
3) Consider the suggestions explained above to address each of the three difficulties.
4) Carefully pick the geologically most plausible solutions. An automatic pick technique doesn't always work well. The horizontal location of the depth symbols is important because it corresponds to the calculated position of the center of the source body (except for the contact model where the position is the corner). Make sure that it is in general agreement with where you would place the center of the body. Again, the experience of an interpreter, familiar with magnetic responses from various geologic situations (and source geometries), becomes invaluable. For example, in Figure 6, a solution near x = 10 000 can be manually and easily picked as a true solution according to the TMI anomaly (and the inclination of the study area), and all false solutions may be rejected. When the differences between nearby depth solutions are great, the anomaly may be complex and one for which the method cannot accurately identify the center or, more likely, the method treated the anomaly as a sum of several separate sources. Choosing between any one of these solutions, particularly in absence of other geologic information, is a dangerous practice. However, if the various solutions are very close to each other, often the average position can be used.
5) Examine the position of the significant anomaly on the image/map of gridded results. The profile should cross the 2D body at right angle to strike and near the center. Otherwise, we need to apply the strike direction correction and the strike length correction. The strike direction correction involves multiplying the estimated depth by the sine of the actual angle between the profile and the strike. The strike length correction is not so straightforward. A simple formula doesn't exist. However, the depth estimate can be directly accepted, when the length of the body is five times the width or more.
6) Compare the solutions for adjacent lines. The interpretation should be internally consistent, particularly for closely spaced lines.
7) Use geologic, geophysical, and well controls that are avail-

able. Magnetic inversion requires constraints, as does depth estimation. Independent constraints are often critical.
8) Use a good 3D visualization tool to display depth solutions. This also provides a dynamic environment to compare various depth estimates and to integrate other geologic, geophysical, and well information.

As an example, Figure 8 shows a field data profile and its final depth solution produced by the comprehensive approach described above. The upper panel displays the raw TMI, filtered TMI, horizontal and vertical derivatives, horizontal and total gradients. Because the deep basement is of interest and there is shallow interference, we have selected Werner deconvolution and Euler deconvolution and assumed the contact geometry. The Bean ratio, a manual method without the use of the moving window, is used to work on selected significant anomalies. Besides automatic clustering, we have picked solutions manually and carefully. The final depth is drawn with consideration of the picks on adjacent lines, and of limited acoustic basement information.

Conclusions. A proper or optimal depth estimate method should be selected according to the data quality and the nature of one's particular geologic problem. From the examples in this article, we can expand this suggestion into three points. First, avoid use of (higher-order) derivatives when noise is strong. Second, understand and determine geometry from geology as much as possible. Third, work on individual anomalies or avoid use of the moving window when interference is severe, as is probable if the results derived automatically are less reliable.

Magnetic depth estimation is a cost-effective and useful tool of quantitative interpretation, and thus helps reduce exploration risk. In order to produce a reliable depth solution, the experience of an interpreter is important and other independent controls are necessary. The comprehensive approach recommended in this article will help derive a final and accurate solution.

Suggested reading. For the theory of different methods for magnetic depth estimation I recommend the following papers. "The direct approach to magnetic interpretation and its practical application" by Peters (GEOPHYSICS, 1949); "A rapid graphical solution for the aeromagnetic anomaly of the two-dimensional tabular body" by Bean (GEOPHYSICS, 1966); and "Automatic determination of depth on aeromagnetic profile" by Naudy (GEOPHYSICS, 1971). "Werner deconvolution for automated magnetic interpretation and its refinement using Marquardt inverse modeling" by Ku and Sharp (GEOPHYSICS, 1983). "The analytic signal of two-dimensional magnetic bodies with polygonal cross-section—Its properties and use for automated anomaly interpretation" by Nabighian (GEOPHYSICS, 1972). "EULDPH—A new technique for making computer-assisted depth estimates from magnetic data" by Thompson (GEOPHYSICS, 1982). "Magnetic interpretation in three dimensions using Euler deconvolution" by Reid et al. (GEOPHYSICS, 1990). "Automatic conversion of magnetic data to depth, dip, and susceptibility contrast using the SPI™ method" by Thurston and Smith (GEOPHYSICS, 1997). "iSPI™—The improved Source Parameter Imaging method" by Smith et al. (*Geophysical Prospecting*, 1998). "Identification of sources of potential fields with the continuous wavelet transform: Complex wavelets and application to aeromagnetic profiles in French Guiana" by Sailhac et al. (*Journal of Geophysical Research*, 2000). "Euler deconvolution of the analytical signal" by Keating and Pilkington (*Geophysical Prospecting*, 2002, submitted). "Unification of Euler and Werner deconvolution in three dimensions via the generalized Hilbert transform" by Nabighian and Hansen (GEOPHYSICS, 2001). R. O. Hansen and his collaborators have developed the multiple-source techniques: "Multiple-source Werner deconvolution" (GEOPHYSICS, 1993), "Multiple-source Euler deconvolution" (GEOPHYSICS, 2002), and "3D multiple-source Werner deconvolution" (GEOPHYSICS, 2003, submitted). The use of Euler deconvolution has been well discussed in "Analysis of the Euler method and its applicability in environmental investigations" by Ravat (*Journal of Environmental and Engineering Geophysics*, 1996). TLE

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