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Quantitative methods for interpreting aeromagnetic data: a subjective review

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Although rapid and relatively accurate graphical techniques exist for interpreting the depth to magnetic sources, these have now been largely supplanted by a wide range of computerised forward modelling routines capable of giving detailed estimates of source geometry as well as the source depth. Computer routines which have automated the depth estimation process also exist; however, these require considerable judgement on the part of the user, as they can give misleading results.

Introduction

The detail in total magnetic data, supplemented by the range of enhanced map and image products typically produced to display these data, normally provides an excellent basis for qualitative interpretations in which geological boundaries and lithologies are visually estimated. Interpretations of this type, which, in effect, produce outcrop or subcrop maps, are routine for areas where all magnetic units occur at or near the ground surface and when anomalies are relatively discrete. Where magnetic rocks occur at variable depth or beneath substantial non-magnetic cover, and where it is essential to know the depth to the magnetic sources, quantitative depth determinations are required. In some cases, specific details of geometry and magnetic properties of the magnetic sources are required and complete quantitative interpretation of magnetic anomalies must be undertaken. This paper reviews methods for determining depth and for performing quantitative interpretation of anomalies. Drawing on the author's experience, the discussion is restricted to those methods which, in the author's opinion, have proved themselves through usage and still have the potential to be widely applied.

Graphical depth determination

Applications of aeromagnetics to the detection and mapping of sediment thickness in sedimentary basins in pre-computer times were based on a range of graphical techniques which rely on the fact that deeper magnetic sources have broader anomalies than shallower sources. Various parameters defining this 'broadness' were measured and related to depth through simple empirical relationships or by the use of graphs.

These methods, and indeed virtually all quantitative interpretation methods, are based on the concept that magnetic sources can, in the majority of cases, be approximated by simple geometric sources. Some authors produced comprehensive atlases of model curves with which to match observed anomalies and thereby arrive at solutions of depth, width, attitude and magnetisation. The Parker Gay (1963) curves for the dipping dyke model, applicable to magnetic bodies with elongated plate-like geometry such as dykes, lava flows, magnetic sediments, basement uplifts and certain ore bodies, are a well-known example of such curves. Manual matching of anomalies to type curves is time consuming and is restricted to the anomaly types for which curves exist. Manual depth determination projects involving many anomalies are much simpler when based on more general models and less elaborate matching procedures. Some of the graphical methods that have been widely used are:

- ***The magnetic pole model*** incorporating point poles, single dipoles, and lines of magnetic dipole poles approximating, respectively, isolated magnetic sources with bottoms at much greater depth than their tops, the general case of isolated magnetic sources, and thin linear sheets of magnetic material. Smellie (1956) showed how to relate the width of such anomalies to the depth of their source (Fig. 1). The problem with such an approach is that wide sources cannot be approximated by the pole model and computed depths will be below the top of the magnetic source because the pole will appear inside the magnetic source.
- ***The prism and horizontal plate model*** developed by Vacquier et al. (1951). This proved much more useful than the pole model, as the prisms approximate a range of intrusive bodies of different width and the plates approximate intrusive sheets, lava flows, and basement uplifts. Vacquier et al. illustrated a series of model anomalies that facilitated an initial visual recognition of likely sources. They also produced simple empirical constants that vary with magnetic inclination, body width and strike and relate the depth of magnetic sources to the 'straight-slope'. This is the distance of the horizontal projection of the apparent straight portion of the steep side of the anomaly (Fig. 1). Despite being based on a visual artefact, the method proved very robust and produced realistic results with the initial delineation of the Gippsland, Bass, Torquay and Otway Basins being a classic example (Haematite Exploration 1965). Case history data suggest that the depth determinations are accurate to ±15 per cent. The weakness of the method is that it is not designed to interpret dipping magnetic bodies.

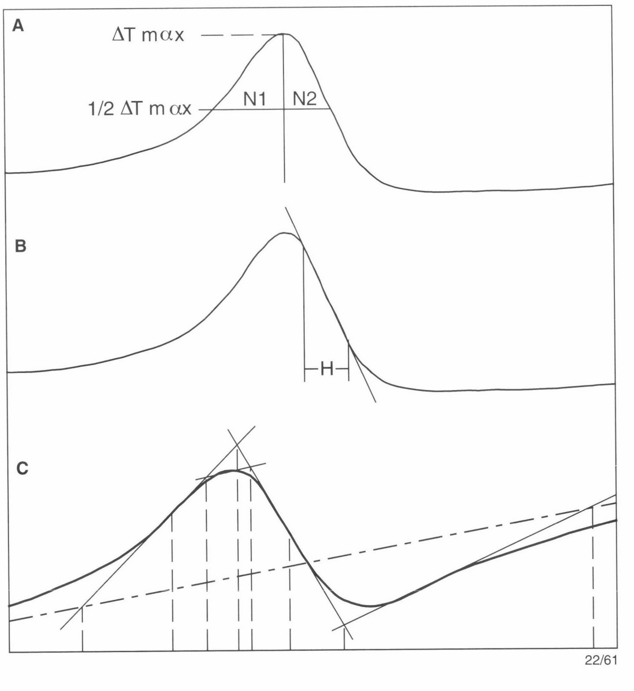

Figure 1. Illustration of parameters measured by graphical depth-determination methods. Depths were determined by relating the parameters to various sets of type curves. (A) the Smellie parameters (1956). (B) The Vacquier et al. (1951) 'straight-slope' parameter. (C) The Naudy (1970) 'ITI' parameters. The horizontal distances between the intersections of the tangents are the critical parameters.

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- ***The ITI (inflection tangents intersection) method*** of Naudy (1970) appears to be the most robust and realistic of all the graphical methods. This method is based on drawing a series of tangents at various inflection points on magnetic anomaly profiles, measuring the horizontal distances between their intersections (Fig. 1), and comparing these to intersections on type curves. As the horizontal distances define the shape of the anomaly, the method is a form of curve matching. Curves exist for vertical gradient and total magnetic intensity profiles and the models that can be interpreted include dipping magnetic sheets (the dipping dyke model), horizontal magnetic sheets, faults and contacts, and prismatic bodies with vertical sides. The method can give the dip of dyke-like bodies if a direction of magnetisation is known. A similar curve-fitting principle is used to estimate magnetisation of the source. The method is independent of linear regionals and the use of logarithmic type curves makes the technique independent of anomaly amplitudes. The method is not widely known because Naudy's original publication was in French and the use of the method was largely restricted to affiliates of Naudy's employer (Compagnie Generale de Geophysique).

The author has been involved with several interpretation projects based on the ITI method, the standard application of which is based on profile plots of total field and computed vertical gradient on 75 cm wide paper rolls. This enables large-scale representation and accurate interpretation of anomalies with amplitudes of the order of one nanotesla. Simultaneous plotting at smaller scales enables the interpretation of any high-amplitude anomalies. All anomalies in a survey area are interpreted on profile data. Subsequent inspection of anomaly trends allows corrections to be made for strike direction relative to the profile and for finite lengths of anomalies. The fact that depth estimates are produced for virtually all anomalies visible on the profile enables detailed contouring of the estimated depths to the magnetic sources. Case study data suggest that the results are accurate to ± 10 per cent. Reford & Butt (1983) reported on the successful ITI interpretation of results from a survey in the Timor Sea–Joseph Bonaparte Gulf area in 1965.

These graphical methods appear to have fallen into disuse, owing to a combination of the unwillingness of interpreters to spend time on them and the tendency to use the variety of automatic interpretation methods described below. It is not certain, however, that many, if any, of the recent interpretations of depths to magnetic sources have been made with the accuracy or detail possible with these graphical methods.

Modelling

The initial *raison d'etre* for graphical depth determination methods was the simple fact that exact modelling of anomalies in pre-computer days required time consuming and tedious manual computation of anomaly forms, using formulae or graticules. With the advent of computers and publication of a series of routines to allow modelling by trial and error, curve-matching processes have become routine. Probably the most significant of the computer modelling algorithms are:

- ***Computation of the magnetic field of a two-dimensional (infinite strike) body with an arbitrary polygonal shape*** (Talwani & Heirtzler 1964). This method calculates the effect of the polygon by summing the magnetic effect of a series of horizontal sheets with sloping edges that correspond to the sides of the polygon. Modelling with the routine is commonly referred to as 2D modelling. Won & Bevis (1987) have produced a faster version of this routine that can handle situations where the magnetic body can be partly above the point of observation and where the observation point can be inside the magnetic body.

- ***Computation of the magnetic effect of arbitrarily shaped three-dimensional bodies by approximating them to horizontal polygonal laminae*** (Talwani 1965). Good results can be produced with this routine (e.g. Gunn 1979), but the process of modifying the corners of the horizontal laminae to match a grid of observations, using a forward modelling process, can be very time consuming.

- ***Magnetic anomaly due to a dipping prism*** (Hjelt 1972). This routine calculates the magnetic effect of prismatic bodies with parallel sides for cases where the top and bottom of the body are horizontal.

- ***Magnetic effect of a body with polygonal cross-section and limited strike length*** (Shuey & Pasquale 1973; Cady 1980). This routine has a significant advantage over the Talwani & Heirtzler (1964) routine in that it enables cross-sections of bodies with finite strike lengths to be modelled with a single profile. The routine assumes that equal portions of strike length occur on either side of the profile being modelled, and that the body being modelled has the same strike cross-section along its complete strike length. Modelling with the routine is commonly referred to as 2.5D modelling.

- ***Magnetic anomaly of a finite-length right polygonal prism*** (Coggon 1976). This routine calculates the magnetic field of a body of arbitrary constant cross-section on a profile perpendicular to the body at any location along the length of the body. Modelling with this routine is commonly referred to as 2.75D modelling.

- ***Magnetic anomaly of a triaxial ellipsoid*** (Clark et al. 1986). This routine is extremely useful for modelling the response of a variety of ore bodies. It is capable of computing the effects of anisotropic susceptibility and demagnetisation. Demagnetisation is an effect whereby the magnetic effects of very magnetic bodies distort the ambient magnetic field such that the direction of the Earth's field changes and the computation of magnetic anomalies using simple induction relationship is no longer possible.

- ***Noddy, a modelling package specifically designed to simulate structural problems*** (Valenta et al. 1992; Jessel et al. 1993). Using this package it is possible to input a series of horizontal layers and then compute the magnetic effect on the stratigraphy after a specified sequence of folding, faulting and igneous intrusion. The routine is based on subdividing the undeformed magnetic units into small cubes. The magnetic effects of the original model and all deformed models are calculated by summing the magnetic effect on the cubes in their original or relocated positions. This package can give useful indications of the likely magnetic patterns in structurally complex areas.

- ***Computation of the magnetic effect of arbitrarily shaped magnetic bodies by approximating their surfaces to a series of triangular facets*** (Bott 1963; Lee 1980). These routines model virtually all situations; however, they depend upon having a routine that facilitates the translation of the shape of the body to the triangular facets. Lee's routine includes the possibility of correcting for the demagnetisation effect if no remanence is present. Lee also addresses the problem of defining the triangular facets.

These routines have been incorporated into various proprietary and commercially available packages of which the most advanced work interactively in Windows-type environments (Fig. 2). These packages allow the interpreter such options as definition of regionals, computation of residuals, multi-source models and inclusion of remanence, demagnetisation and anisotropy. The algorithm used for each modelling exercise depends upon whether the anomalies being interpreted are sufficiently elongated for a two-dimensional or quasi two-dimensional approximation to be used or whether a three-dimensional model is required. The type of three-dimensional algorithm used depends on the form of the magnetic source and the detail required. Such routines have become basic interpretation tools; however, they can be time consuming to apply. They are suited to detailed analyses of single anomalies and clusters of anomalies and cannot be realistically applied to areal depth determination problems.

Inversion

A logical progression from interactive forward modelling was the development of automatic inversion routines that produce a geological model, the magnetic effects of which match an observed magnetic data set. Such inversion routines can either be linear or non-linear.

Linear inversion

Linear inversion techniques (Bott 1967; Safon et al. 1977) consist of subdividing the space below an observed magnetic field into a series of geometric bodies and then finding values of magnetisation for the shapes, such that the summed magnetic effects of all the bodies matches the observed magnetic field. This problem can be formulated as a set of simultaneous equations, in which the known values are the magnetic field at each observation point and the magnetic effect at each observation point, for each geometric body, for the case of unit magnetisation. The unknowns in the equation are the magnetisations of each body required to duplicate the observed field. The problem can be specified as having exactly the same number of bodies as observations, in which case an exact fit between observed and calculated fields will be obtained or there can be more observations than blocks, in which case a least squares solution will be required.

The geometric bodies can have any arrangement; however, most workers use a matrix-type grid of bodies with the objective of obtaining a clustered contiguous distribution of magnetisation values that can be related to a geological entity. In practice, a good fit between observed and calculated magnetic fields is obtained but unless the distribution of geometric bodies is heavily constrained to a probable solution, the magnetisation values bear no relationship, either spatially or numerically to reality. The cause of this problem appears to be related to the fact that truncated samples of magnetic fields are used as input to the problem and the solutions are consequently based on input values that do not necessarily give good representations of the true magnetic field. Linear inversion techniques based on solving simultaneous equations have not found widespread application to interpretation problems.

A variation of the linear inversion technique with wider application has been formulated by Bott (1967). He showed that if the geometric bodies have identical dimensions, and form a continuous layer at a constant depth, then a set of convolution coefficients can be calculated. When convolved with the observed magnetic field, the coefficients will produce the magnetisation of the blocks, provided a correct assumption is made for the direction of magnetisation in the blocks.

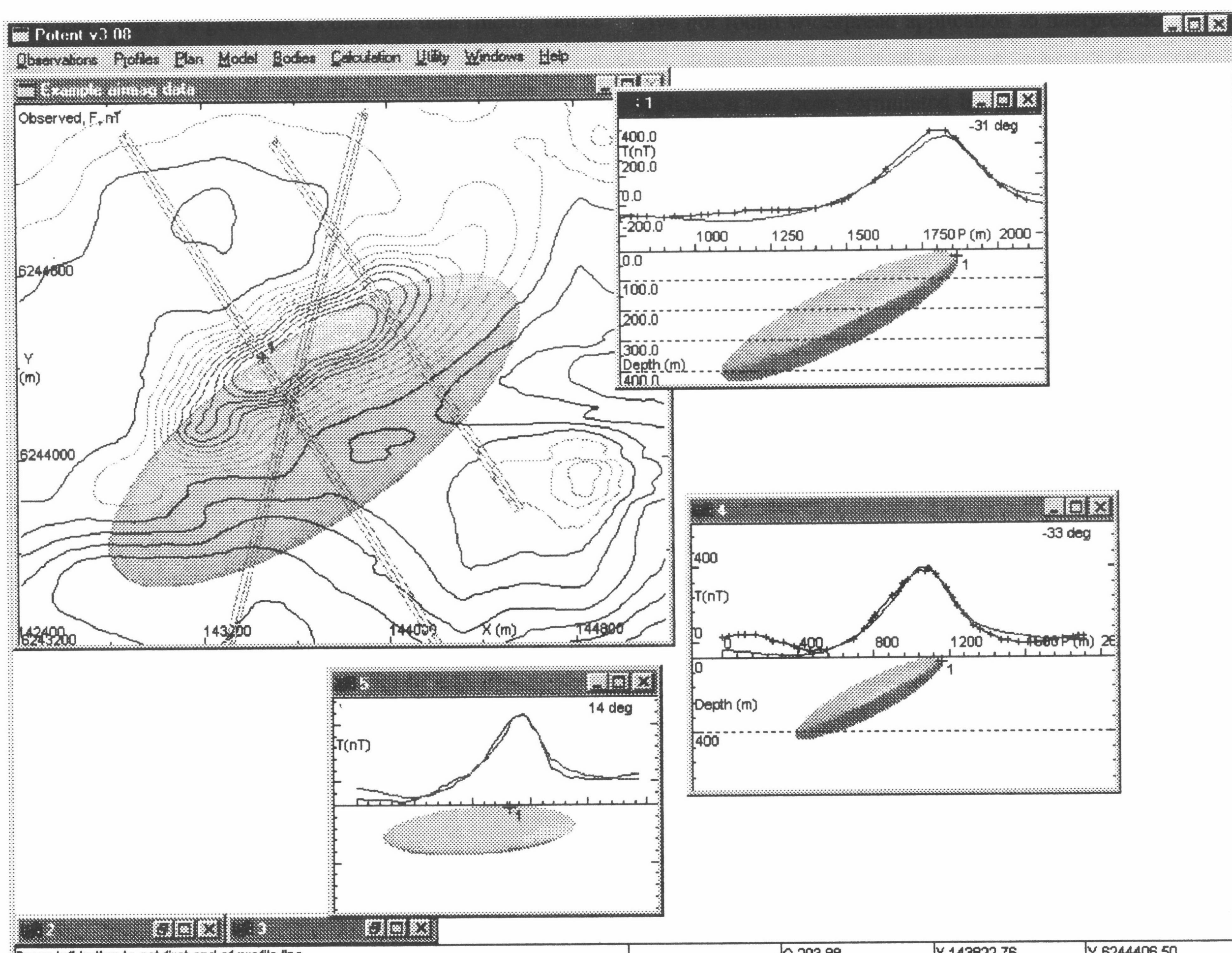

Figure 2. Sample output of an interactive Windows-based modelling package. In the example illustrated, the package was used to select profiles across an anomaly and produced matches at several locations between observed and calculated data using a triaxial ellipsoid model.

Linear inversion using convolution filters (or alternatively, fast Fourier transformation routines) can be used to transform maps or images of magnetic intensity into maps of susceptibility. Such processing, which appears to have moderate usage, allows easier mapping of lithologies than total magnetic intensity datasets. Gunn (1975a) gave the theory for designing such filters in the spectral domain, and (Gunn 1972a) an example of the application of the method to real data for a situation where the results have been verified by ground sampling.

Gunn (1975a) showed that when the relief on magnetic layers with constant magnetisation is relatively small, the relationship between the relief and the magnetic field it produces is almost linear. Gunn (1976) has demonstrated that accurate mappings of such relief can be obtained by the application of convolution filters (Fig. 3).

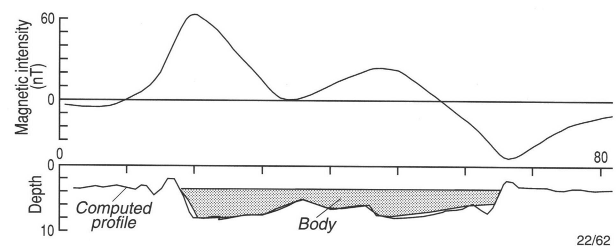

Figure 3. Direct mapping of the relief on a magnetic interface, using a convolution filter (after Gunn 1976). The magnetic profile was input to a filtering routine and the depth profile was output. A knowledge of the magnetisation of the magnetic body being mapped is necessary for the successful application of the routine.

Non-linear inversion

Non-linear inversion (Al Chalabi 1970; McGrath & Hood 1973; Gunn 1975b) attempts to obtain a match between observed and calculated magnetic fields by iteratively varying unknown parameters, such as the coordinates of model bodies and magnetisations. Using a trial and error method, variations that improve the fit between the observed field and calculated results based on the model are stored and used as a basis for new parameter estimates. Estimates that degrade the fit between the observed and calculated fields are discarded in favour of the previous estimate. Such routines consist of an algorithm to calculate the magnetic field of the model bodies plus an algorithm that varies the unknown parameters in such a way that convergence towards a fit between the observed and model fields is obtained. The 'fit' is commonly defined as the minimum of the sum of the squares of the differences between the observed and calculated fields.

Many sophisticated routines exist for estimating parameter variations that lead towards convergence; but a complete description of their characteristics is outside the scope of this paper. It is important to note, however, that the problem is not straightforward, as a simple progressive parameter variation based on successive improvements may not lead to the best fit. A 'local minimum' may be obtained in which both increases and decreases of a parameter value degrade the fit. The best fit or the 'global solution' may require a significantly different value of the parameter. Some non-linear inversion routines are capable of escaping from local mimima.

Non-linear inversion techniques have proved useful in certain well-constrained situations and their application can be much faster than interactive forward modelling. Some geophysicists combine the two techniques and use non-linear inversion to produce the final perfect fit to a solution initially obtained by interactive modelling.

In the author's experience, the main problems with non-linear inversion are that unless the problem is well constrained a solution will be obtained which, although giving a very good fit between the observed and calculated fields, is geologically unrealistic. Most non-linear inversion schemes allow the range of parameter variation to be constrained and it is thus possible to limit such problems. Another common problem involves eliminating secondary magnetic effects from the magnetic values used in the curve fitting. The occurrence of a noise bump or the effects of an adjacent anomaly will not be recognised as such by the matching process and the fit can thus become meaningless. Finally, the calculation of regionals is crucial. This can either be done by the interpreter or left to the routine. Either way, the estimated regional must be real or the interpretation will be unrealistic. Figure 4 gives an example of an interpretation based on a non-linear inversion technique where some of these problems were encountered.

Automatic depth-to-source estimations, using profile data

Several automated methods have been developed to estimate depths to magnetic sources using profile data. All assume that anomalies on the profiles are sufficiently elongated for a

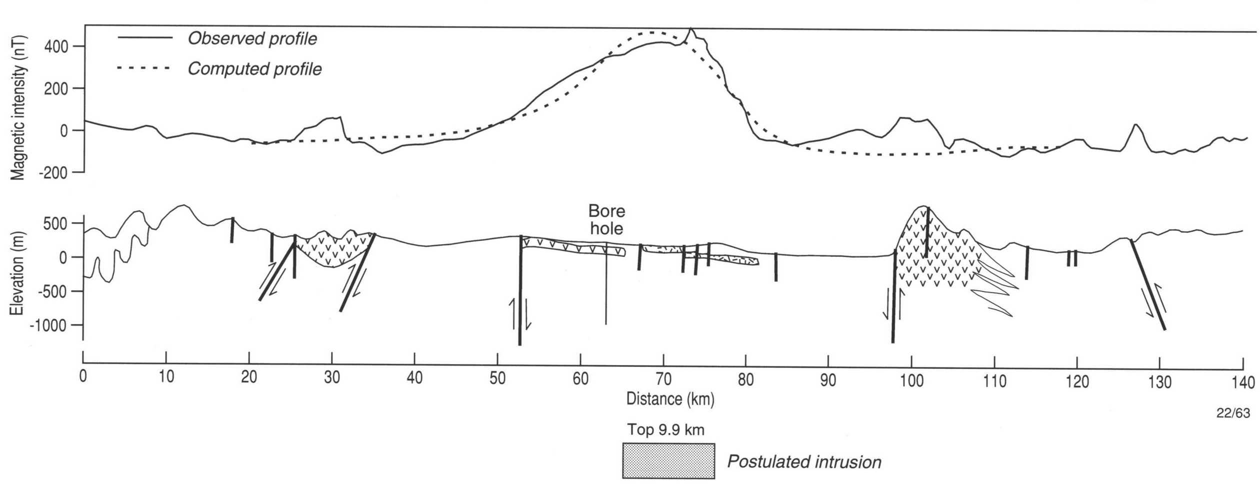

Figure 4. Example of non-linear inversion (after Gunn 1975b). The routine has iterated to find the best match in the least squares sense between an observed magnetic profile and a theoretical magnetic profile due to a prismatic body with a square cross-section. The routine automatically varied the dimensions, depth and magnetisation of the prism and the value of a constant background regional until no further significant improvement in the result could be obtained. The magnetic effects of more than one magnetic body are apparent on the profile. Portions of the profile containing magnetic effects due to shallow magnetic bodies were deleted from the curve-matching process.

two-dimensional assumption to be valid. The most widely used of these methods are:

- ***Werner deconvolution.*** Werner (1953) formulated the magnetic response of a thin dyke with an infinite length and an infinite depth in terms of a linear equation where two of the unknowns are the position and depth to the top of the thin dyke. 'Thin' in this context means that the width of the dyke does not influence the form of the anomaly and, for practical purposes, this applies to all dykes with a depth to their top greater than their width. Obviously, the depth to a thin dyke can be calculated from a set of four simultaneous equations incorporating four different samples of the magnetic field due to the thin dyke. Hartman et al. (1971) extended this idea and produced a more elaborate linear formulation which allows determination of a regional as well as the depth and position of the thin dyke. This elaboration allows the effects of regionals and interference between adjacent anomalies to be accounted for in the calculation of the depths and positions. Hartman et al. used this principle to produce an automatic routine which progressively samples magnetic field values along profiles and determines the depths and positions of all the thin dykes on the profile.

Obviously, not all dykes are thin, however; Hartman et al. realised that the anomaly for the horizontal and vertical gradients over the edges of thick dykes or contacts can be solved using the thin dyke formula and thus they were able to extend their method to these geometries. Horizontal thin sheets are interpreted in the same manner as dipping thin sheets. Different sample intervals are required to solve anomalies at different depths. The results are plotted as symbols on profiles, where the horizontal dimension gives the position and the vertical dimension, the depth. In practice, a scatter of determinations is obtained and virtually all anomalies are interpreted as both thin dykes and edges. Considerable skill appears to be required to use the results in a meaningful way. The concept, however, seems fundamentally sound. Jain (1974), using model data, has shown that the accuracy of the depth determinations is approximately 10 per cent.

- ***'Compudepth'.*** Compudepth is a proprietary method developed by Geometrics for which virtually no documentation is available apart from abstruse mathematical papers by O'Brien (1971, 1972). The method seems to be based on a spectral formulation of the analytic signal (Nabighian 1972). The presentation of the results is appealing, in that it shows a series of positions and depths (together with error bars) of the corners of magnetic sources. A match between the observed magnetic profile and a magnetic profile computed from the interpreted results is also presented. Such matches are generally good and indicate the validity of the results. The method appears to be capable of simultaneously mapping markers at different depths. The author has obtained geologically meaningful results with Compudepth on several projects (Gunn 1979), with some of the results being confirmed by drilling. This appears to be the only published case history supporting the method. However, in other instances the results appeared meaningless. It seems that successful application of the method requires some type of operator controlled tuning to produce optimum results.

- ***Phillips' autocorrelation method.*** Phillips (1979) bases an automatic interpretation method on the assumption that a two dimensional magnetic basement can be approximated by an assemblage of thin vertical or near vertical dykes. Autocorrelation functions of magnetic anomalies due to such dykes have a form that is independent of magnetic inclination and dip and which allows depth estimates to be algebraically calculated using combinations of autocorrelation values at various lags. Consistent depth estimates using a range of different lags are interpreted to indicate a valid depth estimate. Although several organisations, mainly located in the northern hemisphere, appear to be currently using this algorithm, very little published material relating to the routine has appeared in the public domain. Skilbrei (1991) reports using the method but does not include any clear examples of its application in his paper.

- ***Naudy curve-matching method.*** Naudy's (1971) automatic depth-determination routine for application to profile data is based on splitting anomalies into symmetric and asymmetric components, and matching the symmetrical component to the magnetic anomalies of standard simple geometrical forms, such as the dyke, contact and thin plate models. The anomaly that gives the best match is determined by the use of a similarity coefficient. The best match is indicated by minima in the similarity coefficient for a range of models with different depths and thicknesses. The position of the minimum in the similarity coefficient determines the location of the source and indicates the depth of the model. The output is a series of interpreted source depths and locations. Refinements to the method have been made by Shi & Boyd (1991, 1994), who used horizontal and vertical components of the magnetic field as well as the vertical gradient. Unfortunately, the process often produces simultaneous interpretations for all three basic models, but showing different depths. Similarity coefficient values may be output, but the true significance of these is often difficult to determine. The basic problem with the published routines is that the interpreter has no simple way of knowing the validity of any computed depth. This problem has been solved in a proprietary technique developed by Encom Technology Pty Ltd, who have incorporated a forward modelling routine into software based on the Naudy method. The modelling routine enables the checking of solutions and discarding of unrealistic depth estimates. The addition of an inversion routine allows initial depth estimates to be modified to obtain a perfect fit of the field due to the interpreted sources and the observed field (Fig. 5).

Even with the most accurate interpretations of profile data, corrections and correlations with map data must be made in order to obtain meaningful results. Correlation with contoured results is necessary to associate the depth determinations with specific magnetic anomalies. These correlations also enable the discarding of depths determined for short anomalies which do not approximate the infinite strike length assumption. Corrections can be made for cases where anomaly trends are not exactly perpendicular to the profiles.

The Euler depth determination method

A formulation of Euler's homogeneity relationship given by Reid et al. (1990) shows that:

$$(x - x_0)\ \delta T/\delta x + (y - y_0)\ \delta T/\delta y + (z - z_0)\ \delta T/\delta z = N(B - T)$$

where (x_0, y_0, z_0) is the position of the magnetic source whose total magnetic intensity field T is detected at (x,y,z). The total field has a regional value of B. N is a structural index which is equal to three for a point dipole and two for a vertical pipe. More complicated bodies, which are, in effect, assemblages of dipoles, have indices ranging from zero to three. An index of one appears to work for dykes and contacts approximated by lines of poles.

Reid et al. (1990) automated the solution of this linear equation for gridded data to produce solutions for the positions and depths of magnetic sources. By using field and computed derivative values at more points than necessary, they obtained an over-determined set of equations and were able to use least square inversion techniques to solve for the unknowns. The solutions are typically displayed as a series of circles, with the centre of the circle indicating the position of the source and the diameter of the circle indicating the source depth (Fig. 6). The method has proved useful for identifying source

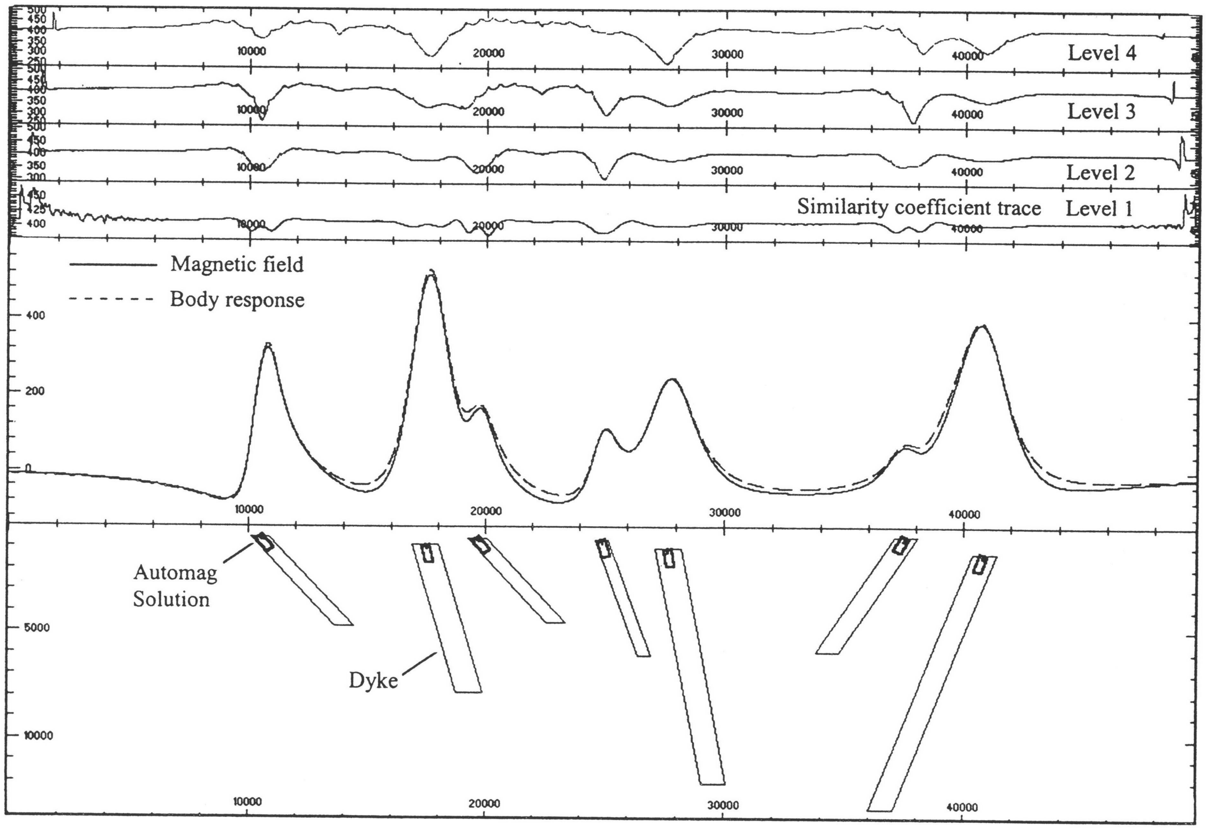

Figure 5. Example of the output of an automatic depth-determination routine based on a modification of the Naudy (1971) method. Initial depth estimates are indicated by minima in the similarity coefficients. The most realistic of these estimates are determined by forward modelling and an inversion routine adjusts the initial depth estimates to give a match of the observed field and the model field due to the interpreted bodies.

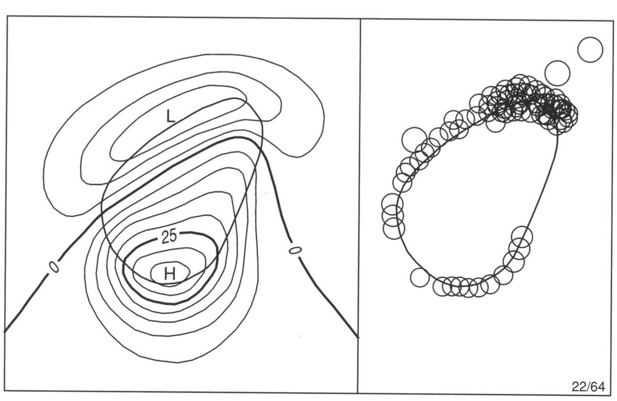

Figure 6. Example of the output of the Euler automatic depth routine (after Reid et al. 1990). The example shows results obtained using the model field over a sill-like body with an irregular outline. The correct structural index of 1 was used. Depth estimates were generally accurate to 13% although some spurious values not related to the body were obtained. Note that not all the body has been outlined.

positions and boundaries and for giving generalised indications of source depth.

From the examples presented by Reid et al. (1990), the method appears to be useful and since the publication of their paper it has been widely used. The author's experience, however, is that, although applications of the method appear to produce meaningful results, these are often difficult to correlate with the true depths and positions of magnetic sources when these are known from other information. Part of the problem in obtaining accurate depths using the Euler method may relate to the difficulty of computing accurate derivatives on which to base the depth estimates. Obviously, noise from shallow magnetic sources will corrupt the gradient estimates for deep magnetic sources, as will wide survey line spacings in areas of high-frequency magnetic anomalies.

The choice of the structural index is critical to obtaining meaningful results and the normal situation, where a survey area contains a range of sources with differing geometry, precludes a definitive processing of an area with a single structural index. Reid et al. (1990) advocated multiple processings with different indices, followed by judicious correlation with anomaly forms. This approach is only partly satisfactory. It may in fact be possible to compute the structural index of a source by formulating the problem to consider the field and its vertical gradient over the maximum of the field at various levels. At the maximum of the anomaly the horizontal derivatives are zero and the only unknowns are the depth, structural index, and the regional. Gunn (1972b) tested this approach on model data free of any regional and found that accurate structural indices were computed. The method was not pursued, because, at the time, the precision of the data required was not generally available. The precision of present-day data should, however, be sufficient, and the idea appears worthy of further investigation.

Analytic signal depth determinations

The analytic signal (Nabighian 1972, 1974, 1984; Roest et al. 1992) is a function related to magnetic fields by the derivatives; i.e.

$$\text{analytic signal, } |A(x,y)| = \left[(\delta T/\delta x)^2 + (\delta T/\delta y)^2 + (\delta T/\delta z)^2 \right]^{1/2}$$

where T = magnetic intensity.

This function is extremely interesting in the context of interpretation, in that it is completely independent of the direction of magnetisation and the direction of the Earth's magnetic field. This means that all bodies with the same geometry have the same analytic signal. Furthermore, as the peaks of analytic signal functions are symmetric and occur directly over the edges of wide bodies and directly over the centres of narrow bodies, interpretation of analytic signal maps and images should, in principle, provide simple, easily understood indications of magnetic source geometry. The half-widths of these peaks can be linearly related to depths, if the sources of the peaks are vertical magnetic contacts.

Roest et al. (1992) have applied the above properties to develop an automated interpretation system, which uses the anomaly peak property of the analytic signal to outline source geometry and the half-width property to obtain estimates of the depths to these sources. Examples presented by Roest et al. (1992) appear impressive; however, there is no way to determine the veracity of their results from their publication.

The analytic function certainly appears to be a worthwhile interpretation tool, but more case-history details are required before its general applicability can be assumed. The author has been involved in several projects where the analytic signal was calculated from map data. In general, sharp anomaly peaks were not obtained over anomaly edges and, instead, diffuse peaks were obtained, whose outlines were less clear than the original total magnetic intensity. Results published by Shuang Qin (1994) appear to support this observation. These deviations of the behaviour of the analytic signal from the ideal case can probably be ascribed to the fact that source geometry was more complicated than a vertical contact. The difficulty of accurately computing horizontal derivatives for small anomalies in directions perpendicular to flight-line directions may, however, have influenced the results. The author's experience with analytic signals computed on closely spaced profile data was more in accordance with the properties of the analytic signal expected from theory.

Analytic signal maps and images are useful as a type of reduction to the pole, as they are not subject to the instabilities that occur in transformations from low magnetic latitudes (McLeod et al. 1994); they also define source positions regardless of any remanence in the sources.

Spectral depth-determination methods

As well as having a form in the space domain, magnetic anomalies have a form in the frequency domain and, in theory, can be interpreted in the frequency domain. In practice, the spectra of single sources and multiple sources are much more complicated in the frequency domain than their space domain equivalents (e.g. Bhattacharyya 1966) and no routine interpretation is attempted with such representations.

The main attempts to use spectral data for depth estimates stem from a publication by Spector & Grant (1970) which was based on the unpublished thesis of Spector (1968).

Spector (1968) showed that for an ensemble of prismatic blocks with infinite depth extent the logarithmic radial energy spectrum of the total magnetic intensity consists of a straight line whose gradient is related to the average depth to the tops of the prisms. Furthermore, in the case of a double ensemble of prisms, two gradients would normally be obvious in the spectrum, with the steep gradient related to the deeper sources and the low gradient related to the shallow sources. It is important to realise, however, that the slope of spectra can only be used to calculate average depths when the sources are an ensemble of uncorrelated magnetic poles. Significant corrections for the average width of the prismatic bodies and their depth extent must be applied before any accurate depth estimation can be attempted for the spectra of ensembles of prismatic blocks. Examples given by Spector (1968) show that these corrections can modify depth estimates by the order of 50 per cent. Spector & Grant (1975) and Spector (1985)

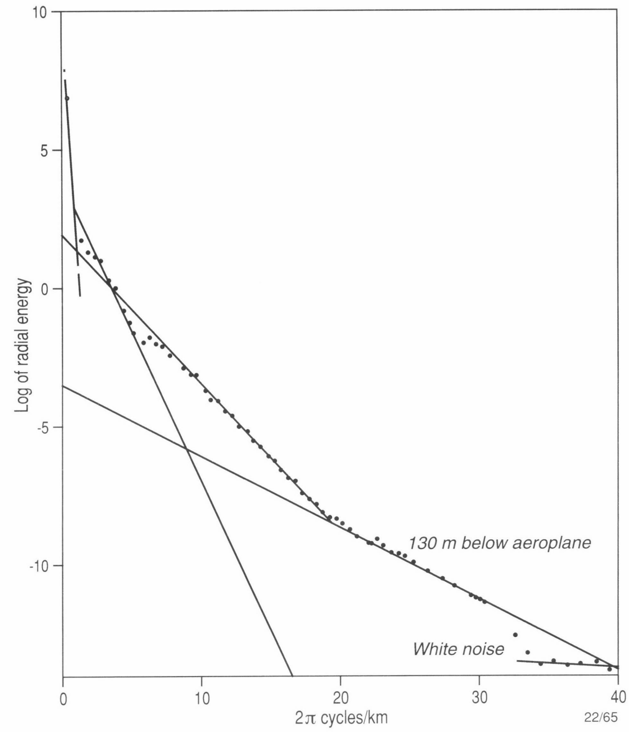

Figure 7. An example of a radially averaged logarithmic energy spectrum of a magnetic field. The spectrum shows straight-line segments, which correspond to 'ensembles' of magnetic bodies with the same average depth. It is not normally possible to calculate the depths of the layers using the gradient of the straight segments unless the average width of the anomalies in the ensemble is known. The shallowest layer is caused by surface culture and its gradient has been related to the flying height of the survey aircraft by assuming that the culture is approximated by a random distribution of magnetic poles.

have published disclaimers, recommending that the method not be used for quantitative depth estimates. Despite this, publications regularly appear in the geophysical literature showing depth determinations based on logarithmic energy spectra with no mention of any refinement to the spectra by the width effect. In practical terms, it is very difficult to envisage how an average body width can ever be calculated in a terrane with elongated magnetic sources. The author has doubts that the approach can be used meaningfully for quantitative depth estimates other than in certain special situations.

The author has computed spectra of detailed aeromagnetic surveys over a sedimentary basin in a heavily populated area of France (Fig. 7). The shallowest linear segments of these spectra can be accurately related to the ground clearance of the surveys, because the magnetic effects of the dense culture in the area approximate a random distribution of magnetic poles. This case appears to be a special situation where the method can be used for the accurate determination of the depth to a magnetic layer.

Cross correlation

For a given digital waveform, the digital filter (subject to the constraint that the energy of its coefficients is unity) that gives the maximum output possible has an impulse response which is the reverse of the waveform being filtered. Such filters, discussed by Treitel & Robinson (1969), are called cross-correlation or matched filters and have application to the automatic interpretation of magnetic anomalies. Figure 8 shows an example from Gunn (1972b) where the anomaly due to a single dyke has been interpreted by a cross-correlation process that correctly gave a maximum correlation when the anomaly

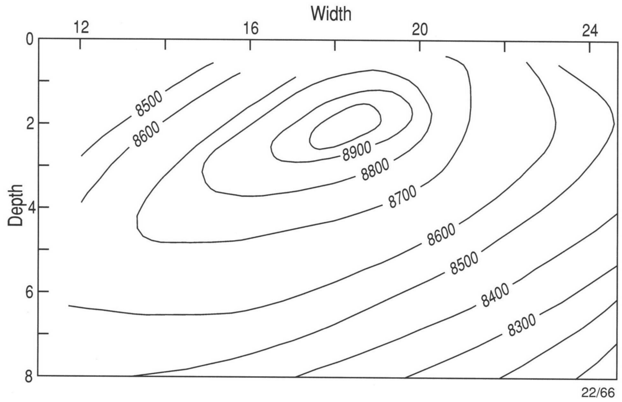

Figure 8. Interpretation of the depth and thickness of a vertical dyke using cross-correlation (after Gunn 1972b). The plot shows filter outputs obtained by convolving the magnetic field of a vertically magnetised vertical dyke, depth 2 units and width 18 units, with the normalised magnetic profiles of other vertical vertically magnetised dykes of various depths and widths. The maximum correlation was obtained for the model with the same depth and width as the dyke causing the anomaly being interpreted.

was convolved with its own waveform. This is the only work on this subject known to the author.

Conclusion

Software available for modelling anomalies can now easily handle virtually every situation. Interpretation, by a trial and error process, provides plausible combinations of body geometry and rock magnetic properties that give realistic explanations for the observed magnetic field. Efforts to automate this process do not appear to provide consistently reliable results. The reasoned judgement of geoscientists is still required to evaluate what is a reasonable solution and what is not.

No published method for automatically calculating 'depth to basement' appears consistently superior to the pre-computer methods used for this purpose. Depth-to-basement maps are probably inferior today compared to those of twenty years ago, owing to the reluctance of interpreters to individually examine every anomaly and to rely instead on 'shotgun' scatters of depth determinations produced by automatic routines. The association of a modelling solution–checking routine with the Naudy (1971) method, as described above, may be the solution to this problem.

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