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AUTOMATIC DETERMINATION OF DEPTH ON AEROMAGNETIC PROFILES†

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In our method of determining depths from aeromagnetic profile data, several sampling intervals adapted to the possible ranges of depths are used for a preliminary analysis of the profiles. This step detects and locates all the anomalies. We then study each anomaly in detail, using several structural hypotheses such as bottomless prisms (dikes) and thin plates. In this way, we produce a series of theoretical structures for each anomaly; only the best-fitting ones are kept. Our results are shown as a distance-depth representation, with the symbols plotted so as to indicate the probable degree of realiability. The complete processing is done automatically by a computer and a plotter.

INTRODUCTION

Comparing measured anomalies with theoretical ones is a good approach for the interpretation of aeromagnetic profiles. The larger the number of points taken for the comparison, the better is the result. The availability of high speed computers gives us an opportunity to test the similarity of measured and theoretical anomalies quickly and objectively.

Perhaps the main difficulty is finding the centers of the anomalies on complex profiles. Analysis of a located anomaly seems to be less difficult. Our processing separates the location and analysis steps.

Some of the ideas used in this paper have been developed by other authors, especially the splitting of the anomalies into two components, symmetrical and asymmetrical (Hutchinson, 1958; Koulomzine et al, 1970), and the reduction to the pole (Baranov, 1957). Our processing uses these methods, together with the classical correlation coefficient.

DEFINITION OF THE COEFFICIENT OF SIMILARITY R

Starting from a curve $y(x)$ and an abscissa s, we can always split $y(x)$ into symmetrical and asymmetrical components; i.e., we can calculate $S_1(x)$ and $S_2(x)$ such that

$$S_1(x) + S_2(x) = y(x),$$
$$S_1(x) = S_1(x'),$$

and

$$S_2(x) = - S_2(x'), \quad \text{where}$$
$$\frac{x + x'}{2} = s.$$

Thus, we let

$$S_1(x) = [y(x) + y(x')]/2$$

and

$$S_2(x) = [y(x) - y(x')]/2.$$

If $y(x)$ has been sampled and if the symmetrical component only is kept, we can associate with each point s a symmetrical curve S_1. S_{1a}, S_{1b}, and S_{1c}, shown on Figure 1, are examples.

The set of curves S_1 is characterized by two parameters: the spacing p between sampled points, and the number $(2m+1)$ of points kept on S_1.

Splitting curves into symmetrical and asym-

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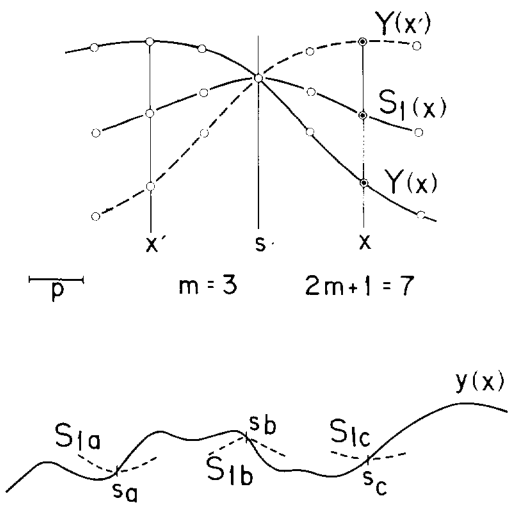

FIG. 1. Splitting any curve into two components.

metrical components is especially interesting when magnetic profiles are concerned, because of the properties of the anomalies from cylindrical (two-dimensional) structures. Figure 2 shows a typical anomaly $f(x)$. If the splitting is done at the center t of the structure, the resulting curves T_1 and T_2 are special ones. Let us suppose, for example, that the structure is a dipping dike, infinite downwards. T_1 and T_2 represent, except perhaps for a constant factor, anomalies given under special conditions by a vertical dike of the same width. These special conditions, are for T_1, a vertical direction of the magnetization and of the measured component of the field and, for T_2, both vectors dipping 45 degrees in a plane perpendicular to the structure.

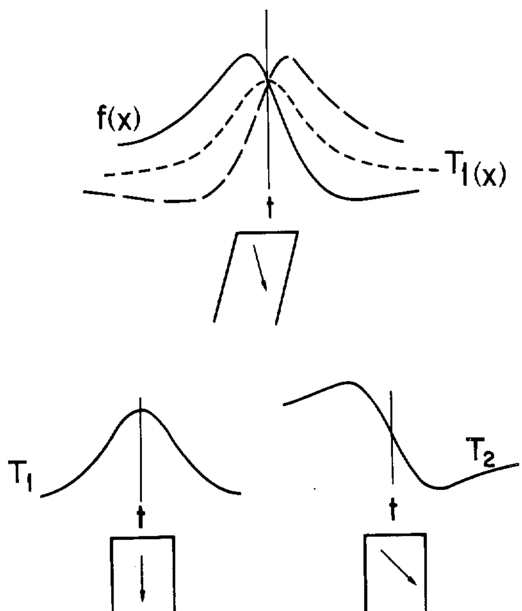

FIG. 2. Splitting an anomaly into two components.

The anomalies given by two-dimensional structures are very common on aeromagnetic profiles. Let us suppose that a profile has been sampled and that the curve S_1 has been calculated for each abscissa s. When s is at the center of an anomaly, the curve S_1 is the component T_1 of the anomaly.

As long as interpretation consists of a comparison of a measured anomaly with theoretical ones, curve splitting allows us to compare symmetrical curves only. In addition, any linear regional anomaly is suppressed.

If only the curves S_1 are kept, half the information in the measurements is lost; for example, anomalies similar to T_2 cannot be interpreted. Therefore, it is necessary to add another processing suitable for anomalies similar to T_2. Reduction to the pole is connected with this problem, since reducing T_2 to the pole gives T_1, except perhaps for a constant factor. Reduction to the pole is generally done on a plane but may be done as well on a profile if the structures are assumed to be two-dimensional and perpendicular to the profile.

Let us suppose that a set of coefficients C_{45} for transforming T_2 into T_1 has been calculated (Figure 3). Convolution of the whole measured profile with these coefficients transforms every anomaly similar to T_2 into an anomaly similar to T_1; such a transformed anomaly may be then interpreted on the transformed profile with the S_1 curves.

Figure 4 shows a measured profile P_u and the transformed one P_v. The effect of the transformation is apparent on the part of the profile surrounding M_u.

In our method of processing aeromagnetic data, a double set of identical calculations are made:

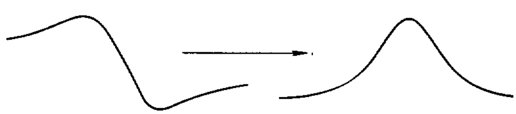

FIG. 3. Effect of C_{45} coefficients.

the first, on the measured profile P_u; the second, on the profile P_v obtained by convolution of P_u with the C_{45} coefficients. At every point, two S_1 curves are independently calculated on P_u and P_v; each one is then compared with a theoretical anomaly T_1. For comparing the S and T curves, we use the coefficients of correlation. If we let $\overline{S}_1$ be the mean value of $(2m+1)$ samples along $S_1(x)$ and $\overline{T}_1$ be the mean value of $(2m+1)$ samples along $T_1(x)$, the coefficient of correlation is

$$r_1 = \frac{\sum (S_1 - \overline{S_1})(T_1 - \overline{T_1})}{\sqrt{\sum (S_1 - \overline{S_1})^2 \sum (T_1 - \overline{T_1})^2}},$$

each sum covering $(2m+1)$ points.

r_1 varies between -1 and 1. The values 1 and -1 are for a perfect similarity; i.e., for two curves S_1 and T_1 identical except perhaps for a constant factor, positive or negative.

For easier calculations, we define

$$R_1 = (1 - |r_1|) \cdot 10^5,$$

which varies between 0 and 10^5, perfect similarity being for $R_1 = 0$.

Two values of R_1, R_u and R_v, are obtained at every point. R_u comes from the original profile P_u; R_v, from the transformed profile P_v. The next step is to find a unique parameter characterizing a point. We define

$$R = \frac{B_u R_u + B_v R_v}{B_u + B_v},$$

which we call the coefficient of similarity and which is the weighted mean value of R_u and R_v. The weights B_u and B_v are the quantities

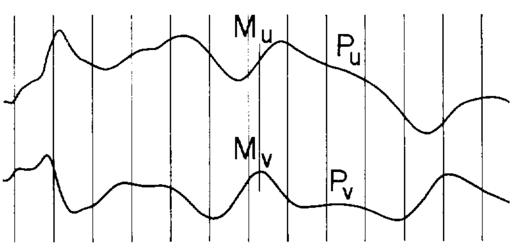

FIG. 4. Convolution of a profile with C_{45} coefficients.

$$B = \sum (S_1 - \overline{S}_1)^2,$$

already shown in the expression for the two r_1's, i.e., r_1 for P_u and r_1 for P_v.

In short, the coefficient of similarity R gives an evaluation of the similarity between a theoretical symmetrical anomaly T_1 and $(2m+1)$ points of a sampled profile. R varies between 0 and 10^5, small values meaning good similarity.

FINDING THE CENTERS OF THE ANOMALIES

After defining the coefficient of similarity, we can describe the processing itself. The first stage is to find the centers of the anomalies. A theoretical symmetrical anomaly T_1 has been chosen as typical of the most frequently measured anomalies. T_1 has been sampled only once and comprises $(2m+1)$ values.

The depth h of the structure giving T_1 may be expressed as a product:

$$h = ep,$$

p being the sampling interval and e, a constant factor. Since $(2m+1)$ samples of a theoretical anomaly have been taken only once, the depth of the corresponding structure is proportional to p.

The measured profile is sampled with successive intervals $p_1, p_2, \cdots, p_n$; and for every interval the following steps take place:

a) The transformed profile P_v is calculated by convolving the measured profile P_u with the C_{45} coefficients.
b) The coefficient of similarity R with the theoretical anomaly T_1 is calculated at every point.
c) The points satisfying the double condition that R is a minimum and $R < R_m$ are kept. R_m is a limit beyond which similarity is too poor for the results to be trustworthy.

Every point kept is the center of an anomaly.

Let us now consider a specific example. Our theoretical anomaly T_1 is that given by a vertical dike infinite downwards, with a width twice the depth (Figure 5). The sampling interval is a quarter of the depth ($e=4$) and the number of sampled points is 29 ($m=14$).

The aeromagnetic profile shown on Figure 6 was sampled with the following intervals: 3, 4, 5, 7, 10, 14, and 20. These numbers constitute roughly a geometrical progression, the ratio of which is $\sqrt{2}$. The unit used for the sampling intervals, as well as for the depths, is the distance flown

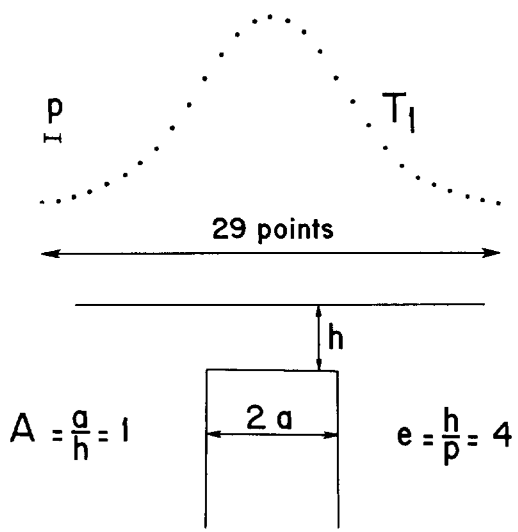

FIG. 5. T_1-locating anomaly.

by the plane in one second, about 80 m, because the magnetic field is recorded with constant time intervals. The limit R_m above which similarity is considered as being poor is 1000.

Figure 6 shows how R varies along a profile for the successive intervals. The minima of R enable the anomalies D, E, F, and G to be located without any ambiguity. The lower plot of Figure 6 shows anomaly centers plotted with a logarithmic scale for the depths. As $e=4$, each depth is four times the sampling interval used for detecting the associated anomaly. This interval is 5 for D, 4 for E, 10 for F, and 14 for G, so that the corresponding depths are 20, 16, 40, and 56.

FINAL DETERMINATION OF DEPTHS

The second part of our processing method takes every point kept in the previous stage and makes calculations which result in a final depth determination.

Let us suppose that in the course of the locating process with the interval p we have found an anomaly center at the point 0. This means that the point 0 may be considered as the center of an anomaly which, sampled with the interval p, is similar to a theoretical anomaly whose symmetrical component is T_1.

At this stage, two questions remain unanswered:

a) Will a higher degree of similarity result if we use an interval q slightly different from p?

b) Is still greater similarity possible if we try another theoretical anomaly instead of T_1? For example, if we keep as our structural hypothesis the vertical dike infinite downwards, quite different anomaly shapes are obtained when the ratio $A=a/h$ is changed. In the expression for A, a is the half-width of the dike and h is the depth of its top. T_1 is the anomaly of such a dike for which $A=1$, but perhaps another value of A would be more suitable for the anomaly being studied.

In order to answer both questions, we calculate tables, an example of which is shown on Figure 7. Each column corresponds to a different value of A: $A_1, A_2, \cdots, A_k$. A value of $e=h/p$ is associated with each value of A: $e_1, e_2, \cdots e_k$. Among the columns is one with $A=1$, $e=4$. The values of e are different for every anomaly; they are chosen so that a set of theoretical anomalies is available.

Each row of the array corresponds to a different value of the sampling interval, $q_1, q_2, \cdots q_l$, where the q's span the value p. For every value of q, with the profile taken around the center 0 of our anomaly, we calculate the transformed profile P_v and the other items of the table. Each one of

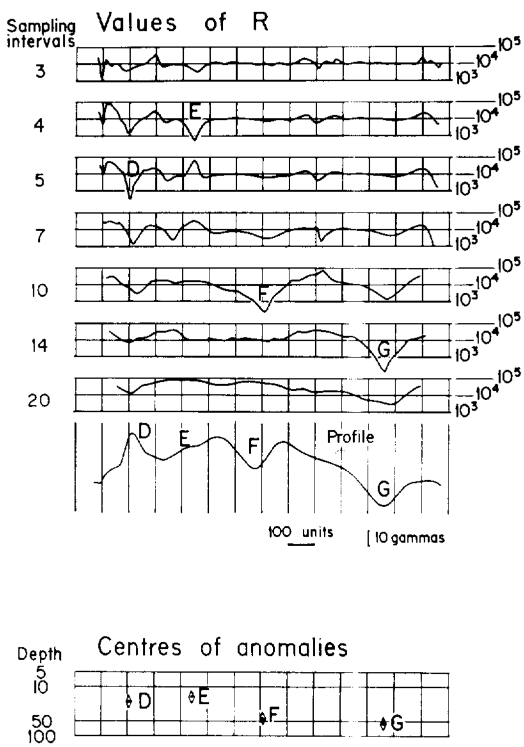

FIG. 6. Values of R along a profile for successive sampling intervals.

these items is the coefficient of similarity $R_{i,j}$ calculated with the anomaly A_i and the interval q_j. We determine the minimum of $R_{i,j}$ for every column; the results are R'_i values corresponding to q'_i intervals. The smallest R'_i and a few other ones slightly larger are kept, together with the corresponding values of q'_i; the latter enable the final depths $h_i = e_i q'_i$ to be calculated.

Again we'll consider a specific example. We use theoretical anomalies given by dikes with the following parameters:

A	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8
e	6.20	5.74	5.16	4.54	4.00	3.52	3.12	2.78	2.50

and theoretical anomalies given by thin plates with the following parameters, the geometrical meaning of which is the same as for the dikes,

A	0.6	0.8	1.0	1.2	1.4
e	6.98	5.73	4.85	4.13	3.60

Either type of structure (dike or thin plate) is processed independently by the computer.

The number of sampled points is 21 ($m = 10$). It is smaller than that for finding the anomaly centers because the remote parts of an anomaly are often disturbed and may alter the detailed analysis. The sampling intervals constitute a geometrical progression with 1.05 as ratio (from $0.746p$ to $1.34p$). The limit R_m is 300, which is smaller than before, as the R values are smaller with $m = 10$ than they are for $m = 14$.

	A_i	0.4	0.6	0.8	1.0	1.2	
	$q_j \backslash e_i$	5.74	5.16	4.54	4.00	3.52	
	9.52	316	288	292	301	354	
p →	10.00	168	144	144	152	195	
q'_i →	10.50	66	46	42	48	81	← R'_i
	11.02	41	26	17	21	41	
	11.57	119	111	99	103	112	
	12.15	335	336	321	327	324	

R'_i	38	21	13	18	40
q'_i	10.8	10.8	10.8	11.0	11.0
h_i	62	56	49	44	39

$h_i = e_i\, q'_i$ final results

FIG. 7. Part of an $R_{i,j}$ table.

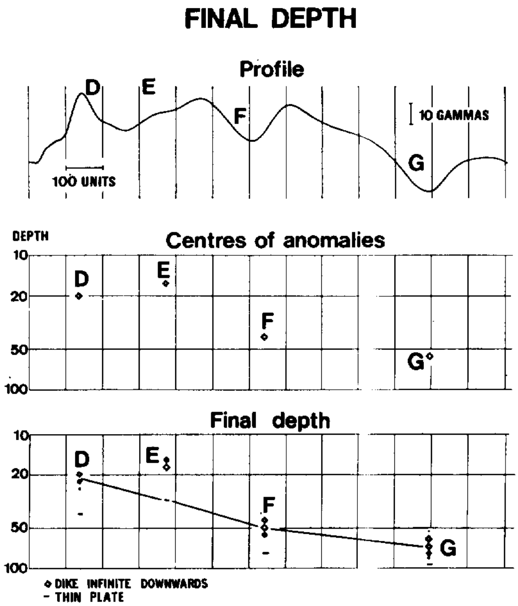

FIG. 8. Final depth.

Figure 8 shows the same profile as Figures 4 and 6, now with the final depths. For each anomaly, the computer using the dike hypothesis has kept the results given by several values of A. The plotted symbols are larger for the smaller values of R. Furthermore, the hypothesis of thin plates has been introduced. The computer and the plotter provide the whole result, except for the line joining the symbols. In this particular case, the interpreter has decided to choose dike models for anomalies D, F, and G and a thin plate model for anomaly E, according to the amplitude of the anomalies.

THEORETICAL TEST

Figure 9 shows the anomalies given by five two-dimensional dikes, infinite downwards. The depths and magnetizations of the dikes are the same (20 for the depth of the top). The values of A ($A = a/h$) are 0.2, 0.6, 1.0, 1.4, and 1.8. For finding the anomaly centers, the following parameters were used: sampling intervals equal to 3, 4, 5, 7, and 10; $m = 14$; and $R_m = 1500$.

The centers found for the structures are exactly the theoretical ones. Each anomaly has been de-

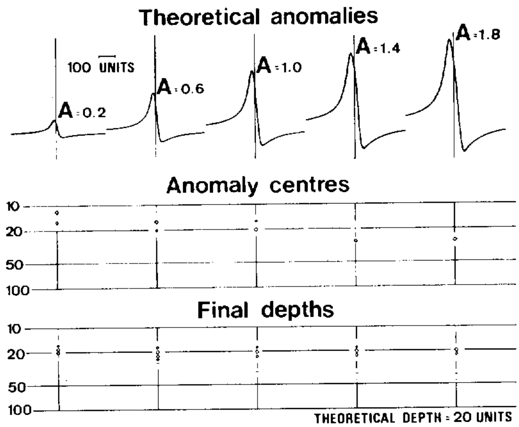

FIG. 9. Theoretical Test.

tected with several sampling intervals, the values of which are different according to the width of the anomalies.

The final depth calculation uses the following parameters: sampling intervals are in a geometrical progression going from $0.746p$ to $1.34p$ with 1.05 as a ratio; $m=10$; and $R_m=200$.

When the final depth calculation found an anomaly center, the calculation modified the depth according to the deviation of A from 1.

For every anomaly, the symbols were plotted on or near the line 20, which shows the actual depth of the five structures.

DETERMINATION OF OTHER PARAMETERS

The depths given by the computer result from the hypothesis that the structures are two-dimensional and perpendicular to the profile. Each depth must be modified to take into account the actual angle shown on the total field map for the directions of the profile and the structure. The total field map may even show that some anomalies are unsuitable for any interpretation with a two-dimensional hypothesis. The results obtained with these anomalies must be rejected.

In the course of the calculations the quantities $\sum (S_{1u}-\overline{S_{1u}})^2$ and $\sum (S_{1v}-\overline{S_{1v}})^2$ have been determined. They were used to calculate the new quantity

$$\sqrt{\sum (\overline{S_{1u}} - \overline{S_{1u}})^2 + \sum (S_{1v} - \overline{S_{1v}})^2},$$

which is proportional to the amplitude of the anomaly.

Each theoretical anomaly A_i has also given

$$\sum (T_{1i} - \overline{T_{1i}})^2.$$

The ratios

$$\sqrt{\sum (S_{1u} - \overline{S_{1u}})^2 + \sum (S_{1v} - \overline{S_{1v}})^2} \Big/ \sqrt{\sum (T_{1i} - \overline{T_{1i}})^2}$$

are evaluations of the magnetization of the structure valid for the hypotheses chosen.

A correction factor is generally necessary to take into account the direction of the structure, the dip, and the demagnetizing field, as long as these parameters can reasonably be estimated.

CONCLUSION

Depth determination is a job suitable for a high speed computer. In comparison with a manual process, computer processing saves time and gives more objective results. However, interpreting an aeromagnetic survey involves something more than a simple depth determination. The experience of a geophysicist is always necessary, whatever may be the part played by the computer.

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