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Spectral Analysis Technique Applied to Magnetic Profile Data for Magnetic Depth Estimates

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Abstract : Many depth estimation techniques for magnetic exploration, such as the slope methods, graphical methods, spectral analysis, and Fourier analysis have been published. Nevertheless, it appears that the half - slope method of Peters(1949)and the maximum - slop method of Vacquier*et. al.* (1951)are more popular and widely used by geophysicists in the hydrocarbon exploration industry. The slope methods are not only simpler and easier to use but are also generally reliable. The spectral mehtod is fast, effective, and powerful in the determination of an average depth. The often unreliable results produced from spectral techniques are attributed to their application to isolated magnetic anomaly cases. The reliability and limitations associated with the method are given in order to minimize problems and increase accuracy in the application of the method.

INTRODUCTION

In hydrocarbon exploration, delineating the crystalline magnetic basement surface configuration is of great importance. Often, a quantitative picture of the thickness of overlying sedimentary rocks can often easily be depicted from the magnetic depth estimates. Possible basement involved structures may also be deduced from magnetic basement surface configurations.

Many depth estimation techniques, such as the slope methods(both the half - and maximum - slopes)(e. g. Peters, 1949 ; Vacquier *et al*, 1951 ; Sokolov, 1956 ; Bean, 1966), graphical methods (Henderson and Zietz, 1948 and 1958 ; Naudy, 1970)spectral analysis(Spector and Grant, 1970 ; Cassano and Rocca, 1975) and Fourier analysis(Ruotoistenmaki, 1987) have been published. Each method has different assumptions, effectiveness, as well as different limitations.

Regardless of popularity of "automatic"computer depth estimation techniques, the slope measuring methods are still widely used by geophysicists in the hydrocarbon exploration industry(Leu, 1981). The reasons are the simplicity and low application cost of the slope methods and the unreliable results which are often produced by "automatic"techniques. It should be noted that an error pointed out by Tarlowski and Koch (1988) in the formulation of Peters' integral equation, has long been corrected by the introduction of the width - to - depth ratio and the proper correction indices of the depth estimator such as by Am (1972) and Leu (1981).

The spectral technique, which is one of the automatic methods, is essentially a statistical method(Spector and Grant, 1970). Therfore, the method can best be applied to the determination of an average depth. The method is fast, effective, and powerful in the determination of an average magnetic depth. Nevertheless, the method has been applied to isolated individual magnetic anomalies (Cassano and Rocca, 1975). Several examples of application of this technique are presented and its reliability and problems associated are discussed.

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DISCUSSION OF SPECTRAL ANALYSIS APPLIED TO MAGNETIC PROFILES

The spatial frequency of magnetic anomalies due to a magnetic body of fixed dimensions in a constant inducing field is a function of the depth to the body ; the deeper the body the lower the frequency (i.e., longer wavelength)of the anomaly. All magnetic (or gravity)depth computation techniques utilize this relationship between the frequency of the anomaly and the depth of the causative body.

For proper application of the graphical and many other techniques, the inducing magnetic field directions must be known, assuming that the remanent magnetizaion is insignificant. Werner (1953) introduced a method which does not require the inducing magnetic field direction in determination of depths and horizontal locations of magnetic bodies.

A relatively new technique, spectral analysis (Spector and Grant, 1970 ; Cassano and Rocca, 1975), provides an estimate of depth to a two - dimensional and / or prismatic magnetic body. This estimate is based on the exponential behavior of the Fourier amplitude spectrum, which is independent of both the horizontal position of the causative bodies and of inclination and declination of inducing field. Bhattacharyya and Leu (1975, 1977)show that their spectral analysis of isolated gravity and magnetic anomalies can accurately estimate the locations of the corners of the polygonal cross section of either two - dimensional structures or three - dimensional rectangular prismatic bodies.

Mathematical expressions of the Fourier amplitude spectra, $|F(\omega)|$, of magnetic anomalies of thin dike - like bodies only contain the depth term, h, in the exponential factor, i.e.,

$$|F(\omega)| = Ae^{-wh} \qquad (1)$$

where, A is a constant.

Taking the natural logarithm of both sides of (1) gives

$$\log|F(\omega)| = \log^{(A)-wh} \qquad (2)$$

The plot of $|F(\omega)|$ against w will therefore be a straight line. The slope of the straight line of the logarithm of the amplitude spectrum then gives the depth to the causative body.

If we square both sides of (1), we obtain the Fourier power (or energy) spectrum. This spectral analysis is called "power spectral density", "power spectrum", or "energy spectrum" analysis. The main difference between the amplitude and power spectra methods in depth computation will be a factor of 2 (or 1/2).

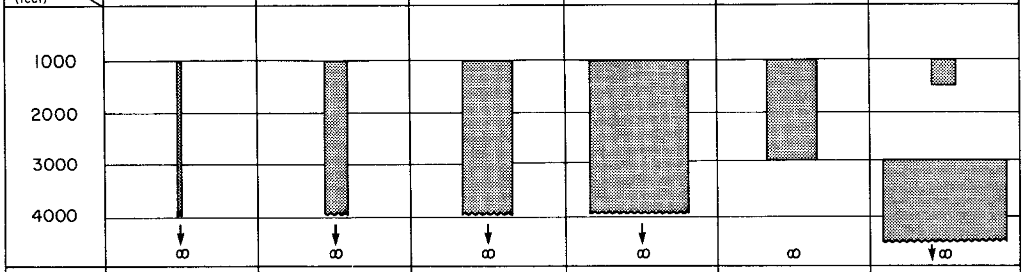
Bhattacharyya (1966) developed expressions for the two - dimensional spectral properties of the anomalies of prismatic bodies. Spector and Grant (1970) extended these expressions to calculate the average depth of one or two prismatic bodies.

O'Brien (1972), in his spectral analysis of magnetic anomalies, attempted to estimate locations of corners of two - dimensional structures by the application of an exponential approximation method. However, he was forced to abandon this approach due to extremely inaccurate results. Bhattacharyya and Leu (1975), however, were able to show that locations of corners of two - and three - dimensional bodies could be accurately determined by spectral analysis. The effects of the bottom edges of the body are mostly concentrated in the low - frequency ends of the anomaly spectrum. Bhattacharyya and Leu (1975) enhanced the effects of low frequencies relative to those of high frequencies by calculating spectra of the first and second moments of the anomaly. This method is a significant improvement over O'Brien's (1972) approach. Bhattacharyya and Leu (1977) extended their method to three - dimensional vertical prisms (i.e., finite vertical extent) with rectangular tops and bottoms. They determined the two horizontal dimensions of rectangular sides in addition to the depths to the top and bottom of the prism. The resulting accuracy of this method is as good as that for the two-dimensional bodies (Bhattacharyya and Leu, 1977).

MODEL EXAMPLES

Three examples of depth calculations for six model that the auther calculated (Table 1) are presented. Depth calculation procedures using a power spectrum are domonstrated. They show (1) characteristics of Fourier amplitude spectrum with various

Table 1. Table showing geological models and their depth estimates.



DEPTH (feet)	MODEL NO.	1	2	3	4	5	6
TRUE DEPTHS		1000	1000	1000	1000	1000 3000	1000 1500 3000
CALCULATED DEPTHS	TOTAL INTEN.	1050	1030	1340	1420 2790	1320 —	1120 1770
	HORIZONTAL DERIVATIVE	790	900	1300	990	1180 —	940 — —

NOTES: SUSCEPTIBILITIES OF CAUSATIVE BODIES ARE ALL 1000 x 10^{-6}cgs.
THE HORIZONTAL SCALE IS THE SAME AS THE VERTICAL.

shapes of anomaly-causing bodies and (2) the advantage of depth calculation using the horizontal derivative for wide bodies.

Figures 1-6 are Fourier amplitude spectra corresponding to the geological models shown in Table 1. Table 1 shows two different depth calculations for each model: (1) depths from total intensity spectra (T) and (2) depths from horizontal derivative spectra (H). It is evident that the Fourier amplitude spectral analyses of horizontal derivatives give better depth estimates for wide bodies (e.g., models 4, 5 and 6), although they resolve only the shallowest depth, as shown for models 5 and 6 in Table 1. However, in the case of model 3, the estimate from the horizontal derivative is not significantly different from that derived from the total intensity profile. It should be noted that for model 4 (a wide body) the depth was overestimated and for model 5 the depth to the bottom surface could not be determined from both the total intensity and the horizontal derivative of the total intensity data.

On each plot of the spectra the depth computation scheme is shown. The depth D to the top of the anomaly-causing body is calcuated as:

$$D=\frac{A\times W}{2\pi}$$

where A is the intercept of the slope with the log amplitude axis and W is the wavelength value (in kilofeet) of the intercept of the slope with the wavelength axis.

Remarks

1. The Fourier spectrum technique is superior for computing an average depth to a group of bodies whose tops lie at similar levels.
2. The minimun acceptable window length for the input data depends on the depth to the top of the causative body. It should be always greater than twice the depth to either the top or bottom of the body.
3. Removal of a regional trend and offsets must be performed carefully in order to obtain a reliable depth estimate.
4. A Fourier spectrum usually yields the depth to

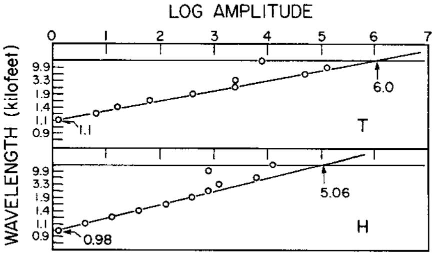


Fig. 1. Fourier amplitude spectra corresponding to the geological model 1 shown in Table 1. T and H in the figure stand for Total intensity and Horizontal derivative of total intensity Fourier amplitude spectra.

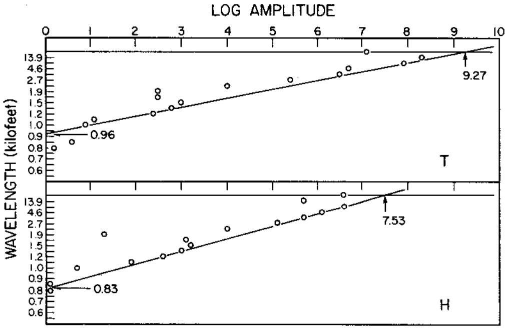


Fig. 4. Fourier amplitude spectra corresponding to the geological model 4 shown in Table 1. T and H in the figure stand for Total intensity and Horizontal derivative of total intensity Fourier amplitude spectra.

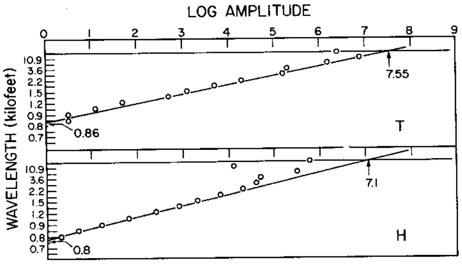


Fig. 2. Fourier amplitude spectra corresponding to the geological model 2 shown in Table 1. T and H in the figure stand for Total intensity and Horizontal derivative of total intensity Fourier amplitude spectra.

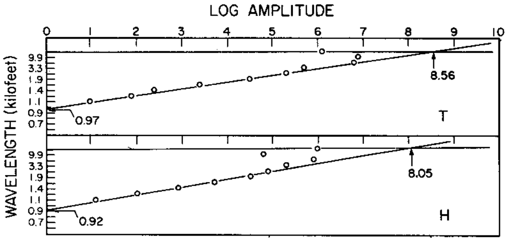


Fig. 5. Fourier amplitude spectra corresponding to the geological model 5 shown in Table 1. T and H in the figure stand for Total intensity and Horizontal derivative of total intensity Fourier amplitude spectra.

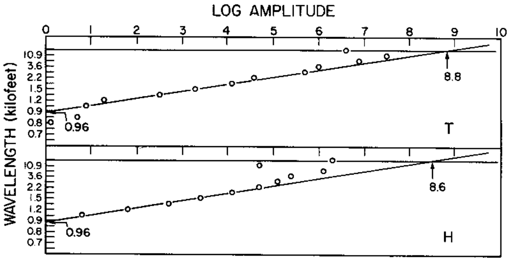


Fig. 3. Fourier amplitude spectra corresponding to the geological model 3 shown in Table 1. T and H in the figure stand for Total intensity and Horizontal derivative of total intensity Fourier amplitude spectra.

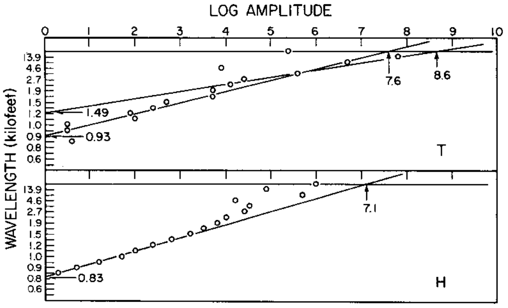


Fig. 6. Fourier amplitude spectra corresponding to the geological model 6 shown in Table 1. T and H in the figure stand for Total intensity and Horizontal derivative of total intensity Fourier amplitude spectra.

the shallowest surface of a body when more than one bodies are involved.

5. Proper windowing and filtering are very important in order to obtain accurate slope(s).

RELIABILITY AND LIMITATIONS

Based on the results of the synthetic data analysis, the following summaries can be made :

A. Synthetic Model Cases

1. One dike

   For a thin dike, the spectrum of the total intensity anomaly itself should be used(e.g. Figure 1 – T). For a thick dike(e.g., Table 1), the spectrum of the horizontal gradient should be used.

2. One twodimensional structure with polygonal cross section :

   Draw a straight line from the spectrum plot, the depth of which will correspond only to that of the shallow elements of the body. A few vertical asymptotes of spectrum may occur.

3. Anomalies of several dikes with the same depth :

   The spectrum of the gradient of the profile is truly exponential and a straight line approximation can be made easily.

4. Anomalies due to bodies of different depths :

   The depth found is, in general, the depth of the shallower body (or bodies) (Table 1) The spectrum of the gradient becomes very complicated.

B. Limitations

1. Finite length of profile(a window length) :

   Minimum acceptable window length depends on the depth of the causative body. Window length should be greater than at least 2 times the estimated depth of the causative body below the magnetometer.

2. Sampling interval :

   The deeper the depth to be estimated, the longer the sampling interval can be. In general, sampling interval should be approximately equal to one–fifth of the depth.

3. Lack of two–dimensionality of the magnetic profile and the angle of profile direction. The approximate effective depth is found by using application of the apparent inclination(Figure 7.).

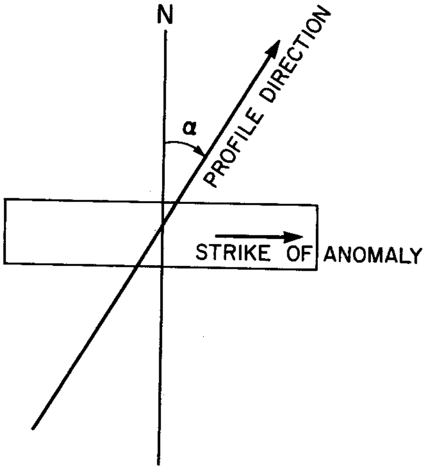


Fig. 7. The profile direction with respect to the strike of a magnetic anomaly is schematically shown. Depth=$D\cos\alpha$; Where, D is the depth computed from the oblique profile. α must be small relative to the length of the magnetic body.

CONCLUSION

No magnetic depth estimation method is truly automatic. With respect to the slope methods the application of proper correction factor is the key to ensure accurate depth estimates. The best assumed indices for the width - depth ratio are difficult to determine since neither the width nor the depth of the causative bodies are known initially. Based on the authors experience in application of the spectral method to both synthetic and real magnetic data the following is considered important in carrying out spectral method.

1. Proper windowing and filtering are essential.
2. The spectrum slope gives the depth to the shallowest body when two causative bodies are superimposed.
3. Composite and overlapped anomalies are difficult to resolve using the spectral method.

4. In general, except for thin dikes, it is better to calculate the spectrum of the horizontal gradient rather then that of the total field intensity profile.

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측선자력의 스펙트럼분석에 의한 자성체 심도추정

박창고 · 박창업

요약 : : 자력탐사 해석에 있어서 Slope, graphical, spectral 및 Fourier 해석 등을 포함한 많은 심도계산 방법들이 연구 발표되었다. 그러나 Peters의 half-slope 및 Vacquier 등의 maximum-slope 방법들이 석유 탐사에 종사하는 지구물리학자들 간에 인기가 있고 널리 사용되고 있다. Slope 방법은 그 적용이 간단하고 쉬울 뿐만 아니라 대체적으로 신뢰성 있는 결과를 준다. Spectral 방법은 평균 깊이의 추정에는 빠르고 효과적이기는 하지만 고립된 개개 자력이상에 적용될 때 믿을 수 없는 결과가 나온다. Spectral 방법의 문제점을 줄이고 결과의 정확도를 높이기 위해서 이 방법의 신뢰도와 적용한계점에 대한 논의를 제시한다.