Geological Mapping by Magnetometer Surveys

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Abstract

Magnetometer surveys are currently being carried out at a very rapid rate for three main purposes: world charts, geological mapping and mineral exploration. Only a small fraction of the data are being given adequate interpretation and a major source of information on the earth's outer shell is being lost.

Improved communication between the different geophysical disciplines is required for the proper growth of the science.

To convert magnetic data into geology the geophysicist must approach the problem three ways: by qualitative interpretation (the geological approach), by quantitative interpretation (the mathematical approach) and by consideration of the properties of rocks and minerals (earth physics).

Numerous examples are available to prove that by intelligent application of geology, mathematics and physics, the end product of a magnetometer survey can truly be termed a geological map.

I. Introduction

A vast amount of aeromagnetic surveying is being done by different agencies in all parts of the world. No accurate estimates of the total line mileage are available but the author considers the figure 5,000,000 line miles per year to be of the right magnitude. In Canada alone, annual survey mileage probably varies between one-half million and one million miles. About one-third of this is done for or by the Geological Survey of Canada for the preparation of low-level aeromagnetic maps at approximately 1/2-mile spacing. Another one-third is done by the Dominion Observatory for the preparation of magnetic charts. This is three-component work, widely spaced, at approximately 10,000 feet elevation. The remaining third is done by private industry in the course of exploration for oil and minerals. While most of these data are processed regularly for their respective applications, in the author's opinion only the last-mentioned one-third are given any serious degree of formal geological interpretation.

Government geological surveys conduct magnetometer surveys to aid in regional geological mapping and to encourage and focus exploration activity. Observatories and other similar agencies carry out magnetic work for the preparation of world charts and to study the magnetic field of the earth. Mining and oil companies

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are interested in the location of minerals. Since the data produced by each of these three groups is generally available to the other two, it seems reasonable to suggest that the studies which are of prime concern to one group make use of the data available from the others.

II. Effective Use of Magnetometer Surveys

Magnetometer data are the raw material upon which feed several geophysical disciplines. Fig. 1 illustrates the functions of three such disciplines and indicates the need for communication between them for the proper growth of the science.

III. Geological Interpretation

The end product of a magnetometer survey is a geological map. The author was asked recently to assist in collecting geological material for the preparation of a geological compilation of a sub-continent. In several parts of the sub-continent large areas had been covered by detailed aeromagnetic survey and subjected to careful formal interpretation. The geologic interpretation that resulted was of major significance: not only did it accurately define surface rocks and structures but, more important, it indicated certain regional features which would have assisted greatly in the regional correlation of rock units and their extrapolation into unmapped areas. The author was more than mildly disappointed when told that the present study was aimed at a geological compilation rather than a geophysical. It...
has always been and still is his impression that a magnetometer survey is just as much a means of mapping geology as are the air photograph and the surface geological traverse.

It is the responsibility of the geophysicist to convert magnetic data into geology. To do this he needs:

1. Experience of magnetic effects of different rocks and structures (qualitative interpretation).
2. Ability to treat data mathematically (quantitative interpretation).

Fig. 2. Effect of decreasing line spacing on aeromagnetic survey and resulting interpretation, Northwestern Quebec.
IV. Qualitative Interpretation

This does not mean merely recognition of anomaly causes. It requires the definition of geologic units and the delineation of geologic structures. Though the quality of the interpretation depends to a large extent on the amount of geological control that is available in the area, some interpretation can always be done even without geological aids. Some of the factors affecting geological interpretation are:

1. Line Spacing

Much has been written about the effect of line spacing on the detection of magnetite bodies [e.g. Agocs, 1955 and Hammond, 1961]. Little emphasis has been given to its effect on the construction of geological maps. Fig. 2 illustrates three aeromagnetic surveys carried out over the same piece of ground in Northwestern Quebec. Line spacings and elevations of the three
Fig. 4. Effect of increasing height on magnetic survey, illustrated by ground and helicopter-borne surveys in Northern Ontario.
surveys from left to right are as follows: 1/2-mile and 450 feet, 1/4-mile and 500 feet, 1,000 feet and 400 feet; contour intervals are 100 gamma, 20 gamma and 20 gamma respectively. The three interpretations shown beneath were done at different times without correlation with one another. The cross-hatched areas indicate steeply dipping bands of basic volcanics. The small areas indicated with the letter M are believed to be basic intrusives. Fold axes are shown in the normal way and a system of northwest-trending faults is shown with a symbol which is used in most of the remaining figures in this paper.

It is obvious that the closer line spacing has resulted in a more complete and satisfactory geological interpretation. In particular, note the development of one intrusive body into three with decreasing line spacing in the southwest corner of the area.

2. Line Direction

Fig. 3 illustrates a portion of a survey flown at low level in British Guiana. The poor definition of the nearly east-west striking bodies A-9, A-11, A-12 and A-13

![Map Image](image-url)

Fig. 5. Effect of topography compounded by alternating line direction, illustrated by helicopter-borne survey in British Columbia.
is due to the choice of an east-west traverse direction. This is aggravated by the
fact that at this low magnetic latitude the steepest gradients normally occur in a
north-south direction.

3. Height

Fig. 4 shows two surveys over some mining claims in Ontario. The survey in
the upper diagram is by ground magnetometer on lines approximately 400 feet apart
with a contour interval of 50 gamma. The lower diagram shows an aeromagnetic
survey at 100 feet elevation by helicopter on more or less the same lines, with a
contour interval of 10 gamma. Magnetic basement was at or near ground surface
in this area. The improvement in resolution of the ground survey is quite apparent.
It is also apparent that by increasing the elevation a better continuity of contours
across the survey lines has been achieved. Line spacing should always be chosen
so as not to exceed the height above the magnetic basement for best geological
interpretation.

4. Topographic Relief

Special problems are encountered in areas of steep topographic relief. These
increase the difficulty of obtaining high quality magnetic data and at the same time complicate the geological interpretation.

Fig. 5 illustrates a low-level aeromagnetic survey by helicopter over an area of steep relief on the west coast of British Columbia. The line spacing is approximately 1/4-mile and the contour interval 25 gamma. The magnetic anomaly falls over a steep topographic feature reaching a maximum elevation of about 3,000 feet. Apart from the effect of the mountain in producing the anomaly, considerable distortion is apparent due to plotting errors in the magnetic data. This effect, called by the
industry "herring boning", is brought about by changes in ground speed of the helicopter when lines are flown in alternate directions. The effect could be removed if the plotting interval was made very close, but in this type of terrain this is seldom possible. The effect can be made more uniform by flying all lines in one direction, but this does not remove the inherent distortion. Flying the survey at greater height by fixed wing aircraft removes most of the distortion but leaves a topographic effect present.

Fig. 6 shows the magnetic effect of topography in another area of British...
Columbia. Observed profiles over a double range of mountains are compared with profiles calculated assuming uniform rock susceptibility. Over the main range, the fit is considered good, the discrepancy on the south flank in the case of the constant terrain clearance profile being due to a greater actual flying height than assumed on that part of the profile. On the north range, a better fit could have been obtained using a rock susceptibility one-quarter of that assumed. Neither of these susceptibilities are unusual for country rocks in that part of the world.

The importance of such topographic effects is that magnetic surveys in such areas must be given much closer inspection before geological inferences are made. It is seldom possible to remove the effects analytically and the interpreter must make careful correlations of magnetic and topographic maps in order to separate intra and supra basement effects.

5. Environment

Other factors not illustrated here include latitude (at low latitudes anomalies look quite different and the interpreter must re-educate himself), rock and structure type (in general, steeply dipping rocks and structures are more easily interpreted than flat ones), complexity, magnetic contrast etc.

Despite the above complications, the geophysicist can usually produce a geologic map which is realistic and sometimes quite accurate. One such interpretation is illustrated in Fig. 7. This is part of a survey in Western Ontario which was interpreted in a routine fashion to guide surface exploration for iron and base metals. Aided by a published geological map at 1 inch equals 4 miles scale, the interpreter has been able to outline accurately several volcanic and sedimentary beds and to indicate the main structural features of the area.

The symbols G, M and E used on the interpretation map indicate known geology, magnetics and electromagnetics respectively as the main basis for the interpretation. Note that the folded band of basic volcanics through Thunder Lake, which provides the key to the structure of the area, is based on magnetics. Several of the granite bodies were partly mapped but have had their limits extended and more accurately defined by the magnetic interpretation. The iron formation was known only in the area west of Thunder Lake prior to the aeromagnetic survey.

The geological map finally obtained was of great value in grading a large number of electromagnetic anomalies detected by the same survey.

Other examples of the routine use of aeromagnetic data in mineral exploration are given by Stam [1960].
V. Quantitative Interpretation

On surveys for iron, quantitative procedures are obviously important. These procedures are well described in the literature, one of the more useful (for small deposits) being that of Smellie [1956].

On surveys used mainly for geological mapping, the importance lies in the identification of anomaly cause through calculation of depth, size, shape and apparent magnetic susceptibility. Methods commonly used for this purpose include that of logarithmic curves [e.g. Hutchison, 1958], half-slope [Peters, 1949] and the dipping dike method [Faessler and Paterson, 1957].

The dipping dike model is particularly useful since it applies to nearly all geological situations on low-level magnetometer surveys. When viewed from a height of 1,000 feet or less, the dike model applies to volcanics, magnetic sediments, sills, dikes, long contacts and many lens-like segregations.

Fig. 8 shows the application of the dipping dike method to the solution of an anomaly outlined by an aeromagnetic survey in British Guiana. The primary purpose of this survey was to provide basement depths for the purpose of outlining zones favourable for bauxite development. The method of arriving at
basement elevation by the dipping dike method is explained on the figure. Two values of “n” and two values of “q” are obtained from pre-constructed master curves. “n” is the ratio of half width of the dike to depth below instrument. “q” is the ratio of the geometric factors multiplying the arctan and logarithmic functions in the dike equation. Only one pair of “n” and “q” provides a solution that is consistent with the rest of the data. A depth to the dike of 470 feet, a half width of 460 feet, and a dip of 4 degrees are determined. The method relies on the measurement of slopes at inflection points and the positions of inflection points and either the maximum or the minimum of the anomaly. These can be chosen in the least disturbed portion of the anomaly; in fact, the method uses less of the anomaly than most other methods. The method is self-checking inasmuch as a body which is not a dike will seldom if ever provide a solution which fits all of the observed data.

Quantitative methods are used in geological interpretation to:

1. Group rocks into different lithologic units.

Fig. 9 shows a comparison of aeromagnetic and geological maps in a Precambrian area in Saskatchewan. It is apparent that a geological interpretation of the magnetic data would have arrived at essentially the same geological map. In fact, there is evidence on the aeromagnetic map of faulting that is not shown on the geological

![Fig. 9. Corresponding geological and aeromagnetic contour maps over a gabbroic intrusion Reindeer River, Saskatchewan. Flight direction: N 75° E. Mean ground clearance: 500 feet. Flight line spacing: 1,320 feet. Contour interval: 25 gammas. (After Slam, 1960)](image-url)
map. However, the purpose of the illustration is to indicate that it is possible, by making susceptibility analyses of the anomalies, to classify the anomalous areas into their correct rock types. Although the susceptibilities of various rocks show wide susceptibility ranges, it is often possible to identify a rock type by its measured susceptibility in a given locality. The susceptibilities here suggest between 3 and 5 percent magnetite in the gabbro and between 1/2 and 1-1/2 percent magnetite in the sediments.

2. Indicate geologic structure.

Fig. 10 shows the geological interpretation of an aeromagnetic survey in Western Ontario. The complicated folding and faulting on the north limb of the structure shown would have been difficult to unravel without quantitative work. As it is, widths and dips were obtainable at several places along both bands of volcanics, suggesting the broad syncline and the superimposed cross-faulting and folding shown.

3. Interpret the geology of mineral deposits.

It is often the case that despite development drilling and even mineral exploitation, the full geological significance of a mineral deposit is unknown. This hampers
development of the deposit and renders further exploration for similar deposits random and sometimes ineffective.

In the example shown in Fig. 11, a body of iron ore, surrounded by ferruginous quartzite, was outlined by drilling. A folded structure of the form shown was inferred. An aeromagnetic profile over the deposit was obtained during the search for similar deposits in the surrounding area. Attempts to match the observed profile using a high susceptibility and the known iron ore indicated that the ore was not the cause of the magnetic anomaly. A solution of the observed anomaly using the dipping dike method provided Body A lying approximately 300 meters below the ground surface. This body is believed to be a wide band (or an isoclinally folded bed) of ferruginous quartzite, the upper levels of which have been altered to hematite and goethite by surface leaching. The actual ore body contributes little or nothing to the observed anomaly.

With this solution in hand it was possible to grade other anomalies in terms of their apparent magnetite content, their depth below surface (the greater depth being the more economically interesting) and their width.

VI. Rock and Earth Magnetism

An understanding of rock and earth magnetism is a prerequisite for a thorough geological interpretation.
1. Regional interpretation.

Fig. 12 shows a regional interpretation of a profile approximately 200 miles long over a Precambrian Shield area. The interpreted geological cross-section and the reconstruction of the Late Precambrian are only one solution to the problem. The shallow Precambrian interpretation is based largely on magnetic contour maps, rather than the profile. The deep structure explains the generalized aeromagnetic profile and provides a mechanism to account for some of the major observed and interpreted features of the area.

Similar regional interpretations have proved constructive in other areas. Data over the Rift Valleys in East Africa are especially revealing. Wilson [1961] has made a similar type of analysis of gravity data over an interesting area in Manitoba. It would be interesting to extend his studies to include the magnetic data also available in that area.
2. Interpretation of complex geological situations (particularly in the presence of strong and reversed remanent magnetism).

Remanent magnetism has been widely discussed in recent literature and correctly so as it plays an important part in magnetic surveys in certain areas. Inverse magnetization is not uncommon and most interpreters can recall cases exhibiting more than one of the normal inversion causes.

Quaternary basalt flows encountered on the San Carlos Indian Reservation in Arizona, for example, consistently show inverse magnetization. The example in Fig. 13 is typical. Here the basalt forms a thin mesa capping, elevated about 100 feet above the surrounding terrain.

In Fig. 14, a complex anomaly in Daubreé and Lévy Townships, Quebec is compared with the published geological map. Since the pyroxenite-peridotite sill responsible for the main anomaly is the host rock for the Opemiska Mine, a detailed understanding of the structure of the sill was obviously desirable. The aeromagnetic data were immediately useful in this respect, particularly in the area along the common boundary of Daubreé and Lévy Townships. In this area two strong anomalies, one negative and the other positive, were interpreted as the north and south limbs of a folded structure. The negative anomaly over the north limb is believed to have been caused by structural deformation rather than by inverse magnetization. Detailed ground surveys were conducted and numerous oriented

![Fig. 13. Corresponding geologic and aeromagnetic contour maps over basalt mesa-capping in Arizona, Illustrate effect of inverse polarization.](image-url)
samples were taken before this theory was accepted and used in the subsequent exploration program.

3. Detailed Interpretation of ore deposits.

The effects of remanence and demagnetization must always be taken into account in the detailed analysis of grade, tonnage and body geometry of magnetite deposits. The complex situations arising in certain deposits of hematite and ilmenite [e.g. Howell, 1962 and Carmichael, 1962 and 1959] require even more careful study.

VII. Final Geological Interpretation

The main requirements of the final interpretation are as follows:

(1) It should be consistent with the observed magnetic data.

Fig. 14. Corresponding geologic and aeromagnetic contour maps, Oopeniskaj Mine area, Northern Quebec, show complex pattern over folded, strongly magnetic rocks.
(2) It must account for all major magnetic effects (anomalies, trends, discontinuities etc.) even if the interpretation is only one of several possible.

(3) It must be geologically reasonable.

(4) It should be consistent with known geology but not necessarily in every detail (e.g. the magnetic data may reflect events occurring beneath the surface rocks; geological maps are not always correct).

(5) It should state clearly the assumptions, ambiguities and inaccuracies.

VIII. The Need for More Interpretation of Magnetometer Surveys

At the risk of digressing in an otherwise largely technical symposium, the author wishes to make a final plea for more emphasis on the interpretation of magnetometer surveys.

We are challenged domestically and internationally by dwindling mineral resources. There is a wealth of useful geological information buried in existing magnetometer surveys. This includes surveys flown at high level for charting purposes.

An unique opportunity exists for geophysicists of all nations to aid in the vast geological mapping and mineral search program in underdeveloped countries. However, we as geophysicists must guard against recommending surveys in areas where their application, by virtue of topographic relief and other causes, is doubtful.

An enormous amount of useful data on the earth's crust and upper mantle is available in existing magnetometer surveys. Huge projects are underway to collect geophysical data to further our understanding of the earth. Similar attention should be given to the adequate analysis of data already available in our files.

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