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RECORD No. 1962/38

REPORT OF VISITS TO U.S.A. AND CANADA, 1961

(with particular reference to methods of aeromagnetic interpretation)

by

J.H. Quilty

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1. INTRODUCTION

Between January and March 1961 an official visit was made by the author to certain government organisations, oil companies, and airborne survey contracting companies in U.S.A. and Canada.

The purpose of the visit was to study techniques of interpretation of aeromagnetic data, particularly in relation to oil exploration, and to attend a course in aeromagnetic interpretation at the United States Geological Survey in Washington.

The itinerary was as follows -

Jan. 7	Departed Melbourne.
Jan. 9 - Jan. 16	Visited Los Angeles (Union Oil Co.).
Jan. 16 - Jan. 22	Visited Houston (Humble Oil Co., Geophysical Associates Inc., Rice University).
Jan. 22 - Jan. 26	Visited New York (Standard Vacuum Oil Co.).
Jan. 26 - Jan. 30	Visited Philadelphia (Aero Service Corpn.).
Jan. 30 - Feb. 6	Visited Ottawa (Canadian Geological Survey, Spartan Air Services Co., Canadian Aero Service Co., Dominion Observatory).
Feb. 6 - Feb. 13	Visited Toronto (Rio Tinto Co., Hunting Survey Co.).
Feb. 13 - March 20	Visited Washington (U.S. Geological Survey).
March 22	Arrived Melbourne.

A short visit was made to Rolla, Missouri, between 24th and 26th February to attend an International Mining Symposium.

This Record contains the notes on discussions with specialists of the various organisations; the discussions dealt with airborne surveying in general and aeromagnetic interpretation in particular, with emphasis on its application to oil exploration. Notes on other matters such as analysis of magnetic properties of rocks, properties of sedimentary rocks, age determinations of rocks, analysis of oil samples, and problems in interpretation of gravity data are also included.

The last five weeks of the visit were spent at the office of the U.S. Geological Survey in Washington D.C. where the author attended a course of instruction in magnetic potential theory and development of formulae for calculation of magnetic fields, techniques of magnetic interpretation, and case histories of magnetic surveying.

A summary of developments in techniques of aeromagnetic interpretation is included in this Record.

2. VISITS TO ORGANISATIONS

UNION OIL CO., Los Angeles

(Messrs E. Babson, J. Sloat, M. Sklar)

All aeromagnetic surveys for Union Oil Co. are done by contracting companies, but the Union Oil geophysicists interpret the results. The aeromagnetic work is detailed, with small flight-line spacing even over deep sedimentary basins, to ensure that each magnetic gradient is recorded. Reconnaissance surveys are not favoured. Their geophysicists admit that aeromagnetic reconnaissance has some value in giving a broad regional picture of unexplored areas, and they use such data when available in a preliminary assessment of new leases.

The company requires the contractor to provide aeromagnetic data which are as free as possible from error, with drift, heading effects, and parallax kept well in control instrumentally. Reduction procedure is to be strict to obtain good closures on the tie systems. In practice, the standard of the survey operations and the quality of the aeromagnetic maps appear to be largely in the hands of the contractor. A typical map is produced at a scale of 1 mile = 1 inch, with a contour interval of 5 gammas.

The interpretation is done on the total intensity anomalies, working on the contour map and not on the recorded traces (profiles) because the map shows the steepest gradients which may be obscured on the traces because of flight-line direction. Second vertical derivative maps are sometimes prepared to aid in delineation of anomalies that might have structural significance; these maps are not used for depth estimation of basement rocks. The aeromagnetic map is examined for anomaly patterns characteristic of certain rock types, for marked changes in patterns indicative of contacts between rock types, and for discontinuities in elongated anomaly forms due to cross faulting.

Estimates of depth to basement rock are made by measurements on the anomalies. Each interpreter favours a certain parameter for measurement. One parameter used is the horizontal extent of the maximum gradient, this being considered to be equal to the depth of the magnetic source. Anomalies are carefully selected for this measurement. Another parameter is the horizontal distance between points of half the maximum slope. This distance is considered to be equal to the depth multiplied by a factor of approximately 1.6. Estimates based on these measurements have been found to be reasonably accurate.

A contour map of depth to basement rock is drawn. This map also contains geologic information deduced from the anomaly patterns as described above. The interpreter may mark certain areas where low-amplitude anomalies are considered to be due to relief on the basement surface. The depth contours are examined for the major changes in the elevation of the basement surface and for flexures in the contours where basement relief may produce significant sedimentary structures.

UNION OIL RESEARCH LABORATORY, Brae, Los Angeles

No specific investigation of the magnetic properties of rock samples is done at present in this laboratory. Magnetic separation methods are used in the classification of hornblendes and in the determination of magnetite content of sedimentary rocks.

A research programme conducted by R. Gees includes a photographic analysis of mineral assemblages in sedimentary rocks. Techniques used are X-Ray diffraction and fluorescence, and examination of thin sections to determine pore space, grain size, and grain sphericity. Powdered specimens are fed to a magnetic separator, where a fine separation of the magnetic minerals is made on a vibrating plate enclosed by an electromagnet.

Core samples are cut with a diamond drill attached to a conventional workshop drilling machine. Cores are subjected to measurement of bulk volume, pore volume, gas permeability, and pore volume continuity (American Petroleum Institute, 1959).

In equipment designed to measure seismic bar velocities, the core is held by springs between two elements, a fine oil film being used as a coupling at the contacts. Pulses at the rate of 100 per second supplied by a pulse generator are converted to longitudinal vibrations at the ends of the core. Travel time of these vibrations through the core is recorded on a cathode ray oscilloscope.

Infra-red spectroscopy is used in the examination of oil samples, and comparisons are made with the results of standard specimens to determine the properties of newly discovered oils.

GEOPHYSICAL ASSOCIATES INC., Houston

(Dr L. Nettleton, Dr N. Steenland)

Gravity anomalies

Dr Nettleton prefers uncomplicated methods of interpretation of gravity anomalies, and demonstrates them in his treatment of anomalies recorded in the Gulf, where the sources are believed to be salt domes.

The process of constructing a gravity residual map by removal of the regional gradient from the original gravity map is either a graphical one, involving "smoothing" of contours or profiles, or a numerical one obtained by calculation on a grid of gravity values. The various methods in current usage are described by Nettleton (1954).

Representative profiles of the residual anomaly under investigation are drawn with the profiles of adjacent anomalies, the contribution of which is subtracted from the main anomaly profile. The final stage is the construction of a cross-section to reproduce the residual gravity profile. In the example of the Gulf area, the cross-section is of a simple dome with slight alteration to the semi-circular top to adjust for asymmetry in the residual gravity profile.

Comparisons of graphical residuals, gridded residuals, and derivatives using different grid spacing are shown in the above paper.

As a general rule Dr Nettleton considers that for size of grid spacing to be used in residual or derivative calculations, the radius on which field values are averaged should approximately equal half the average radii of the anomalies.

Aeromagnetic anomalies

Steenland's interpretation of aeromagnetic anomalies is based on the characteristics of the anomalies due to two different types of magnetic bodies. The first of these is the prismatic model with vertical sides extending to great depths, i.e. the model of Vacquier, Steenland, Henderson, and Zietz (1951). Observed anomalies are compared with the standard anomalies of Vacquier, and appropriate indices are chosen for depth estimation. It is claimed that certain indices are independent of the inclination of the polarising field and therefore can be used for anomalies other than those due to induction in the present Earth's field.

The second type is that approximating a horizontal plate or sheet. The anomalies due to these bodies are much smaller in amplitude than those of the prismatic type; they have a different form and require the use of different depth indices for depth estimation. Some anomalies due to plates or sheets are described by Zietz and Henderson (1956).

The anomalies of Vacquier et al (1951) were redrawn and partly recalculated for ease in interpretation. A set of anomalies for sheet or plate bodies was evidently constructed, and suitable parameters selected as depth indices.

Steenland claims that the assumptions of homogeneous magnetisation and of vertical sides of structures are surprisingly valid, and that his depth estimates are accurate to within 6 per cent. He believes the next development in aeromagnetic work should be towards more sensitive recording of the magnetic field.

Depth estimates are made on the original magnetic profiles, due correction being made for obliquity of the flight-line direction with the direction of magnetic gradients. Faults, contacts, and possible basement relief are marked on the map. (Other organisations claim that Steenland over-interprets the magnetic data, particularly in regard to interpretation of basement relief from minor anomalies).

HUMBLE OIL RESEARCH GROUP, Houston

(Dr Rust, Dr Miller)

A group at this laboratory is measuring magnetic remanence of rock samples, using the "spinner" techniques on weakly magnetised specimens and the deflection of magnets suspended on torsion fibres for specimens with higher magnetic remanence. Magnetic susceptibilities are measured by placing the samples in magnetic field coils. Small cylindrical samples of the rocks are cut for these measurements. A more complicated version of the "spinner" equipment, in which the specimen can be rotated in two directions, has been designed to compensate for the softer components of magnetic remanence, e.g. due to lightning in rock samples.

Dr Miller uses models of Vacquier et al. (1951) in the interpretation of aeromagnetic anomalies and suggests that recalculation and redrawing of the standard anomalies would make them more useful. His approach to the problem of variation in inclination of the magnetising field, or in shape and orientation of the magnetic body under investigation, is that if an observed anomaly can be closely fitted to one of the standard anomalies, the selected model represents at least one solution for the source of the anomaly. This is considered a justification for using models under various conditions of magnetisation, direction, etc. for depth estimation.

Humble Oil geophysicists believe that interpreters in some contracting companies take their interpretations of basement rock depths and structures beyond reasonable limits.

STANDARD VACUUM OIL CO, New York

(Mr Gwynn, Mr Gilson, Mr Caan)

This company's method of interpreting aeromagnetic data was shown in a report on a survey in the Bengal Basin. Observed anomalies were compared with standard anomalies of Vacquier et al. (1951).

and when a reasonable match was obtained, indices were selected and measured for depth estimation. A table showed the standard anomaly, depth index, and depth estimate used on each observed anomaly. These operations were carried out on the total-intensity anomalies.

In certain parts of the area, second vertical derivative maps were constructed to obtain a greater resolution of anomalies, and depth estimates were sometimes made on the second derivative anomalies.

AERO SERVICE CORP., Philadelphia

(Mr R. Hartman, Mr C. Isaacs)

Interpretation of magnetic maps has been based on the models of Vacquier et al. (1951). The standard anomalies therein were redrawn and recalculated.

Observed anomalies are matched with the standard anomalies, and indices are selected for depth estimation. Evidently the indices used did not conform rigidly to those described by Vacquier; corner indices were found to be useful (Corner indices have been used also by one interpreter at Union Oil Co.).

In survey operations, Aero Service has used G.P.L. Doppler navigating equipment, evidently with successful results. There is still some doubt as to its satisfactory performance over water, and at low altitudes over land. It is considered that Marconi Doppler equipment may be more successful at altitudes of 500 ft or less (Canadian Aero Service has installed Marconi doppler in an aircraft for airborne electromagnetic survey in Surinam, where flying altitude is to be approximately 300 ft).

In plotting of flight lines from photo-navigated surveys, readily identifiable surface features are plotted from the strip film to the aerial photos or photomosaics, and these points are joined by straight lines indicating flight paths. The separation of these plotted points is probably not less than 2 to 3 miles.

A scaling machine has been built to transfer details of contour level intersections on the magnetic profile of the chart directly to the flight-line plot.

CANADIAN GEOLOGICAL SURVEY, Ottawa

(Dr L. Morley, L. Collett, A. Gregory, A. McLaren, Miss M. Bauer)

Aeromagnetic maps of Canadian Shield areas are being interpreted by A. McLaren. The object is to determine structure and lithology and to locate ore deposits from a study of the intricate magnetic pattern. Correlation of magnetic data with known geology, and field checks on rock types, form part of the investigation. Magnetic properties of rocks are measured in the laboratory.

One method used in the interpretation is the colouring of various magnetic intensity ranges on the map to aid in the correlation with outcrops. Another method is to colour the intensity ranges in various shades of red, and then to photograph on panchromatic film at reduced scale. This technique shows clearly geological trends over large areas. Second vertical derivative maps are constructed in some areas to give greater resolution of anomalies.

The Canadian Geological Survey has a plan to cover the entire Canadian Shield by airborne magnetometer survey in the next twelve years. The survey operations and making of the aeromagnetic maps will be done by Canadian private contractors. The work will probably be shared between the Spartan, Hunting and Canadian Aero Service companies.

The sedimentary areas of Canada have been surveyed aeromagnetically by private companies, and the results of these surveys for the most part are not available to the Geological Survey. The aeromagnetic data of one sedimentary area was interpreted by staff of the Survey. Depth estimates were based on comparison of observed anomalies with models of Vacquier et al.(1951) and the use of the prescribed indices. The estimates compared fabourably with known depths to basement from bore-hole data. The use of Peters' half-maximum slope parameter, with a factor of 1.6, was shown to give fairly satisfactory estimates also.

CANADIAN GEOLOGICAL SURVEY LABORATORIES

In the palaeomagnetic laboratory, remanent magnetism of rock samples is measured, using the "spinner" technique or an astatic system of suspended magnets. Before these measurements, samples are "cleaned" of soft remanent effects in magnetic field coils. Magnetic susceptibilities are measured in a commercially made meter (price 9000 dollars).

Age determination of samples is done, using the potassium-argon or rubidium-strontium method. X-Ray diffraction and fluorescence, and mass spectograph methods are used to determine mineral content of samples; they are used also to test micas for presence of chlorite, which influences measurements in age determination.

SPARTAN AIR SERVICES, Ottawa

(Mr G. Shaw, W. McPherson)

This company uses the proton magnetometer in aeromagnetic surveying. The recorded profile is a reciprocal reading of the magnetic field value and requires a special scaling device to convert to the actual value.

Equipment was installed in the survey aircraft to produce a 7-hole digital punched tape recording of the magnetic field, with a view to reduction of the data by electronic data-processing methods. It was found that considerable noise in the output of the magnetometer, which would be smoothed manually on the recorded profile in hand-reduction methods, was recorded on the punched tape and interfered with reduction by electronic computer. Evidently because of this problem, it was decided that data processing of the record was not an economic proposition. However it was mentioned that if navigational information could be incorporated in the punched tape recording, an overall data processing of geophysical and positional information would be considered worth-while.

The present objective is to correct the analogue record of the proton magnetometer for diurnal variations in the magnetic field. The output of storm warning (proton) magnetometers on the ground in the vicinity of the survey area will be transmitted to the survey aircraft and recorded as a secondary profile on the airborne magnetometer record; or the two recordings will be integrated to produce a corrected recording of the airborne magnetomer. Diurnal variations of the magnetic field are large in Canada, and often swamp the effects of instrumental error.

In certain future surveys, proton magnetometer records, corrected for diurnal variation, will be used directly without any reduction. At present a tie system is still flown across flight lines.

Spartan are awaiting the results of tests now being made by Canadian Geological Survey with direct-reading proton magnetometers.

Spartan geophysicists have not had experience in interpretation of the aeromagnetic data.

<u>DOMINION OBSERVATORY</u>, Ottawa

(Dr Niblett, Dr Whitham)

This group is investigating magnetic storms, including the distribution of magnetic variations over large areas. A practical application of this analysis should be to determine maximum distance between ground monitoring magnetometers and the airborne magnetometer in survey operations.

<u>CANADIAN AERO SERVICE CO.</u>, Ottawa

(Mr M. Reford)

<u>Doppler navigation</u>

Canadian Aero Service Company's opinion of Doppler navigation is best summarized by the following extract from "Airborne magnetometer Surveys for petroleum exploration" by M.S. Reford :

"It is when the base maps are inadequate, or when there are few recognizable features on the ground, that a navigation aid is needed. The first choice is Doppler navigation since it requires no ground stations. The instruments in the aircraft measure the true track and the distance travelled, with an accuracy better than 1%. The pilot's instruments show the distance of the aircraft to the right or left of the desired track, so that he can fly lines that are almost perfectly straight and in the proper locations. Fiducial marks are added to the records at chosen intervals of distance rather than time. The Doppler information caneven be used to control the speed of the recorders, so that the records will have a constant scale with respect to the ground. In recovering the flight path the strip film is used in the normal way, and full photographic coverage is desirable. However, it is not necessary, for the flying is so accurate that only key points need to be identified. This reduces the work considerably, and one of the big advantages of a Doppler system is that it lends itself to field compilation and interpretation of the magnetic data. The interpreter may be able to see that some lines are unnecessary, and can be dropped from the programme, while extra lines should be added to give more information over critical areas. Another advantage is that the strip films can be used to control air photographs, and accurate base maps may then be constructed.

The Doppler system does have a weakness. Over water its accuracy may decrease to about 3% as a result of currents and calibration shift. This is not a serious weakness provided that lines do not extend more than some 20 miles offshore. Beyond that point it may be advisible to turn to one of the electronic aids involving ground stations, such as Shoran, Decca or Raydist. These involve a considerable increase in cost, unless stations are already operating in the area. Shoran has the special advantage of giving geodetic control information for making very accurate base maps. All of these systems will speed up the process of flight path recovery over visual methods."

Interpretation methods

Mr. Reford recommends the use of original charts , where available, for depth estimation. Maximum gradient rule and Peters' half-maximum slope rule are recommended. Where the aeromagnetic map only is available, the construction of a second vertical derivative map or simply a residual map is used for delineation of significant anomalies. Based on the apparently correct claim that the residual map has the same form as the derivative map, residual anomalies may be quantitatively interpreted from indices of the derivative anomalies given by Vacquier et al (1951).(The weakness in all measurements made from constructed maps is that the anomalies are very subject to the grid spacing selected for the map construction.).

Where the maximum-gradient and other depth rules are used on anomalies due to bodies whose thickness is smaller than the depth of burial, the estimated depth will probably be about two-thirds the actual depth.

A study of the amplitude (intensity) of the anomalies will give an idea of possible susceptibility of material in the bodies, and may help to distinguish supra-basement from intra-basement bodies.

HUNTING SURVEY CORP. Toronto

(Dr N. Paterson, F. Jacoditz, A. Rogers)

Tie control flying

The two types of tie control in aeromagnetic survey are used by Huntings.

In each system the flight lines are crossed at right angles. by control (tie) lines spaced 6 miles apart. In the simpler of the two systems, a single-line control loop is then flown about an area of size 36 miles x 36 miles. In the other system, double-line control loops are flown on four sides of a square, 18 miles x 18 miles.

The intersections of control lines with control loop are phot-matched in the plotting procedure. The flight lines are "laid" into the grid of control lines in the reduction.

In surveys where great accuracy is not required, single ties are flown across the ends of the flight lines and the datum levels of the lines are adjusted by a "tilt and difference" method.

Tolerance for diurnal variations in aeromagnetic survey are as follows :- 2 gammas per 2 min for flight traverse lines, 7½ gammas per 5 min for all control lines. The camera used in the aircraft is the 35-mm Canadian Applied Research Mk 8.

Photo plotting

In a typical photo plot, features are identified on the film and transferred to the photo-mosaic at intervals of approximately two miles, and straight lines are drawn between these points. When base-lines have been fitted to the chart profiles and the contour level intersections have been marked, these intersections are transferred to the flight-line plot with the aid of a paper strip, scale differences between chart and plot being adjusted by appropriate projection of the paper strip on the plot. Herring-bone trends in magnetic contours are investigated, but where no reason can be found for them in the reduction process, these trends are included in the final map.

<u>Interpretation</u>

The following methods are used in the interpretation of the aeromagnetic anomalies

(1) Pole and Line Theory (Smellie)

(2) Vacquier <u>et al</u>. (1951) models.

(3) Dipping dyke and symmetrical dyke diagnostic properties.

(4) Dyke, scarp or thin bed properties (Hutchison).

(5) Half slope measurements (Peters).

(6) Curve matching.

<u>Pole and line theory</u> is described by Smellie (1956).

<u>Dipping dyke and symmetrical dyke</u>. Curves have been prepared which relate diagnostic properties of anomalies (e.g. horizontal distances between maximum and inflection points) to the depth, width, and dip of dyke structures.

<u>Dyke, scarp or thin bed properties</u> An analysis of anomalies due to the above structures is described by Hutchison (1958).

<u>Curve matching</u> here probably refers to the method of constructing a magnetic model to fit the observed anomaly, and amending it by trial and error.

All measurements are made, where possible, on the original profiles, allowance being made for direction of flight line and scale of profiles.

<u>RIO TINTO CO</u>., Toronto

(H. Seigel)

Most of the aeromagnetic interpretation has been concerned with metalliferous areas. The method of interpretation is mainly based on the properties of anomalies due to elongated near-vertical tabular magnetic bodies. Two measurements are made on each anomaly; namely, the horizontal extent of the maximum slope distance on each side of the anomaly profile. A set of curves is used which relate these parameters to variations in width, dip, orientation of body, and inclination of polarising field.

Airborne electromagnetic surveys are made with transmitter and receiver coils mounted on wing-tips of aircraft, the axes of coils being in the direction of the aircraft heading. In-phase and quadrature components of the field are measured at a frequency of 320 c/s.

In combined magnetic, electromagnetic, and radiometric surveying, the following data are recorded on 6 channels on a Bush recorder (Cleveland, Ohio) :- (1) Magnetometer (2) In-phase electromagnetic (3) Quadrature electromagnetic (4) Altimeter (5) Accelerometer (6) Scintillometer.

In electromagnetic interpretation, the emphasis is on the in-phase component record. Anomalies are graded on amplitude and slope and given the classification - 1A, 1B, 2A, 2B, 3, X in decreasing order of significance.

UNITED STATES GEOLOGICAL SURVEY, Washington.

The U.S.G.S. has provided much of the material on which aeromagnetic interpretation is based.

Calculation and model studies

The calculation of the total-magnetic-intensity field and the second-vertical-derivative fields due to prismatic bodies with vertical sides extending to great depths in the basement complex was done jointly by the Columbia University Geology Department and the Geophysics Branch of the U.S. Geological Survey. The results were published in the Geological Society of America Memoir 47 (Vacquier *et al.*, 1951).

The magnetic effects of horizontal laminae were investigated. Model studies were made, and some results were published in a paper by Zietz and Henderson (1956). Calculations on these models are continuing.

The effect of remanent magnetisation on aeromagnetic anomalies is being studied by calculating the total magnetic intensity fields due to bodies magnetised in fields of various inclinations and declinations. The results of this work have not yet been published.

The total-intensity anomalies due to magnetic doublets were calculated, and factors were determined by which the depth to the upper pole and the length of the doublet could be obtained by measurements on the anomalies. Model studies on cylinders and slabs of magnetic material showed that these bodies could be treated as magnetic doublet equivalents, providing the cross-sectional area was small compared with the depth of burial. The results are published by Henderson and Zietz (1958).

Graphical techniques

Pirson polar charts, drawn at appropriate scale, are used for the calculation of the magnetic effect due to two-dimensional sources. The evaluation of the total-intensity anomaly field by the use of these charts is a simpler procedure than the evaluation of the components of the field.

A modified Gassman integration procedure for use in evaluation of the total-intensity anomaly due to a three-dimensional body of arbitrary slope is described in a paper by Henderson and Zietz (1957).

The Henderson-Wilson polar chart is used for evaluation of total-intensity anomaly due to three-dimensional bodies. The body is divided into a series of laminae, and the magnetic contribution of each is graphically evaluated from the chart.

Use of electronic digital computers

Programmes have been devised for calculation of magnetic effects of bodies by digital computer. Three-dimensional bodies are simulated by a collection of blocks of different shape and size. The contribution of each block to the magnetic anomaly is readily calculated in the computer programme. The formula for calculation of the magnetic effect of the individual blocks was derived from the gravity formula. The magnetic effect can be shown to equal the gravity effect of the block minus the gravity effect of the same block when moved a short distance along the direction of the total field (Poisson's Theorem).

Interpretation - special projects

In many special interpretation projects carried out by the Geological Survey, the magnetic effect of natural bodies such as sea-mounts, granitic buttes, etc is studied by a comparison of the observed anomalies over them with calculated anomalies of bodies of the appropriate physical dimensions. The method of calculation is either a graphical one or a computation normally done by electronic data processing methods as described above. In those projects, results of other geophysical methods such as gravity measurements are correlated with the magnetic data.

Interpretation - sedimentary basins

Estimates of depth to basement rock are based on measurements of gradients on the observed anomalies and comparison with the characteristic gradients of anomalies calculated for idealised bodies such as prismatic bodies.

A parameter favoured for measurements by Mr Zietz is the horizontal extent of the maximum gradient, this being considered to be equal to the depth to the surface of the prismatic body. This measurement is made only on anomalies of considerable areal extent.

The magnetic contribution of relief on the basement surface is recognised. Such relief can produce anomalies of small amplitude at the observation level. The calculated effects of horizontal laminae, simulating basement relief, have been studied and it is known that depth rules (such as horizontal extent of maximum gradient equals depth to body), produce incorrect depth estimates when used on such anomalies.

In general, the U.S.G.S. is not prepared to ascribe basement relief features to observed minor anomalies, or to use these anomalies for reliable depth estimates, because of the uncertainty as to the nature of the source.

As mentioned previously, the U.S.G.S. has studied the effect of remanent magnetisation on aeromagnetic anomalies. Some maps show positive and associated negative anomalies, indicating low inclination of polarising field, in areas where the inclination of the Earth's present field is high. Calculations are being made on idealised bodies with varying angles of inclination and declination.

Results to date show that on these anomalies ;

(a) the line joining maximum and minimum is an accurate indication of the declination of the polarising field,

(b) a relation exists between distance from maximum to minimum and the inclination of the polarising field, and

(c) these anomalies are amenable to the depth rule of horizontal extent of maximum gradient equal depth to body.

Where the areal extent of the anomaly is small, indicating a prismatic source with cross-sectional area small in comparison with depth, the analysis can be made in terms of a magnetic doublet (dipole).

3. SUMMARY OF DEVELOPMENTS IN INTERPRETATION

(1) The current practice in aeromagnetic interpretation is to analyse the recorded total-magnetic-intensity data, either in profile or contour form, rather than to resort to constructed maps of residuals, second vertical derivatives, or mathematical space continuations of the field. These constructed maps are sometimes used for qualitative interpretation, but all quantitative work is done on the total intensity data.

(2) The analytic approach to interpretation, in which the data are analysed directly to yield the configuration of the source, is rarely used. Most work is based on the synthetic approach, in which the anomalous field due to idealised configurations is built up for comparison with anomalies observed in aeromagnetic surveying. There are several ways in which these idealised data are built up, and in which they are then used.

(3) The idealised data are built up by calculation using the appropriate formulae for potential fields, by model studies, or by graphical techniques using prepared polar charts. The calculation of the anomalous field due to two-dimensional magnetic bodies, i.e. those which are elongated sufficiently to be considered infinite in one direction in the horizontal plane, is a reasonably simple task provided the vertical cross-section of the body is a regular shape. Adequate formulae for these calculations are in textbooks such as Heiland (The results of these calculations are illustrated in a set of booklets prepared by the Airborne Reductions Group of the Bureau). Where the cross-section of the two-dimensional body is not of regular shape, the use of a graphical method (the Pirson polar chart) is recommended.

(4) The calculation of the anomalous field due to three-dimensional magnetic bodies of regular shape is an involved and time-consuming task, which has been simplified in recent years by the use of electronic computers. The first album of anomalies due to prismatic bodies was published by Vacquier <u>et al</u>. (1951). The anomalies due to horizontal sheets or laminae have been calculated, and some of the results are in published literature. The anomalies due to prismatic bodies magnetised in a direction other than that of the Earth's present field are in the course of calculation and will be published.

(5) Polar charts, e.g. the Henderson-Wilson chart, have been devised for graphical evaluation of anomalies due to three-dimensional magnetic bodies of irregular shape. Electronic computer programmes were also prepared for the computation of magnetic anomalies due to these bodies; the shapes of the bodies are simulated by collections of magnetised "blocks".

(6) The synthetic data obtained by the above methods have one use in the process of analysing anomalies by curve matching. This procedure is not normally used in regular interpretation of metalliferous or sedimentary areas, but is valuable in special studies of observed anomalies. The calculated anomaly is matched to the observed anomaly, and the idealised body is successively modified until reasonable agreement is obtained. The modifications can be done by simple addition of laminae and their anomalies, by recalculation in electronic computing routines, or by reshaping of models in graphical techniques.

(7) The wider use of the synthetic data is in its application to the problem of depth determination and possible structure determination, in the interpretation both of sedimentary basins and of metalliferous regions. Here the data are analysed to find diagnostic properties, of the calculated anomalous fields, related to the depths and also the configurations of the magnetic bodies.

(8) Many aeromagnetic surveys of sedimentary basins in U.S.A. and Canada have been successfully interpreted by a comparison of the observed anomalies with the album of anomalies by Vacquier et al. (1951), followed by the use of depth indices that relate the horizontal extent of various gradients on the anomalies to the depth to the surface of the magnetic structures. It is concluded that the prismatic shape of the models in the album is a reasonable approximation to the shape of many magnetic structures in the basement rocks of sedimentary basins.

(9) Certain "rule of thumb" or "express" methods have derived from the above studies. For example, some interpreters make depth estimates based on the rule that the horizontal extent of the maximum gradient observed on anomalies of considerable areal extent is equal to the depth to the surfaces of the magnetic structures. Another rule used is that the horizontal extent between points of half the maximum slope (gradient) of the anomalies is equal to approximately 1.6 times the depth to the surfaces of the magnetic structures.

(10) In some Canadian companies, the method used has been to prepare, for graphical use, families of curves that relate the diagnostic properties of anomalies due to magnetised vertical or inclined tabular sheets to the width, depth of burial, and dip of these bodies. The diagnostic properties selected are usually the horizontal extent between maximum points, points of inflection, etc. of the anomalies. Attention is drawn also to the treatment of pole and line-of-pole problems by Henderson and Zietz and later Smellie. Magnetic doublet analysis is described in a publication by Henderson. A paper by Hutchison proposes a special approach to analysis of anomalies due to scarps, thin beds, and dykes(see References).

(11) Though most observed anomalies are probably due to magnetic contrasts within the basement rocks of sedimentary basins, these contrasts evidently being simulated satisfactorily by prismatic models, the contribution of basement relief alone to the observed magnetic pattern has been studied. Calculations of the anomalous field due to horizontal laminae show that these bodies, which would simulate basement relief, can produce anomalies of measurable intensity at the level of observation. Where clearly developed, these anomalies would be characterised by enclosing associated negative anomalies. In airborne surveys they are often superimposed upon larger and more intense anomalies and there is no certainty whether they are due to basement relief or minor intra-basement contrasts.

(12) Between the divergent views of interpreters on the treatment of these small observed anomalies (up to 20 gammas)(Jacobsen, 1961), a reasonable approach would be to interpret the more clearly delineated ones on the map as representing possible areas of basement relief. From calculations on the model laminae it is known that depth rules used on the gradients would generally produce depth estimates smaller than actual depths. The estimates, however, would probably be of the same order as those obtained on the more intense anomalies.

(13) An associated problem is that of a second magnetic horizon, such as a sill-like body, producing interference in the magnetic pattern due to the basement rocks. This is normally resolved by the contrast in depth estimates based on anomalies of the two origins within the area of investigation.

(14) In many rocks the remanent magnetisation exceeds the induced magnetisation. Where the direction of remanent magnetisation approximates that of the Earth's present field in the area of investigation, the characteristics of the resultant anomaly are the same as if the body were magnetised by induction only, except that the intensity of the anomaly is greater. The anomaly is directly comparable with the album of anomalies calculated for induced magnetisation effects for purposes of depth estimation.

(15) Where the remanent magnetisation is appreciable and is in a different direction from that of the inducing field, the characteristics of the resultant anomaly are no longer comparable with the calculated induced effects. These circumstances are simulated by calculations on prismatic models with varying directions of polarisation (U.S. Geol. Survey). This work is not yet complete. The results to date indicate that a good deal of information concerning inclination and declination of the remanent magnetisation may be gained from a study of the relative positions of the observed positive and negative anomalies on the map. It also appears that for depth determinations these anomalies may be amenable to depth rules such as horizontal extent of maximum gradient equals depth to body.

(16) A contour map of depth to basement rock in sedimentary basins is normally prepared, using the depth estimates on the individual anomalies. The map also shows any geological information which may be deduced from the magnetic patterns. For example, granitic rocks often produce an array of circular anomalies or "bird's eye" anomalies of moderate intensity. Basic rocks often produce intense elongated forms. Metamorphic zones of older rocks are often characterised by intense circular anomaly forms. No attempt is normally made to mark the map with the supposed rock type, but lines of contact are drawn along interpreted boundaries. Large-scale faulting of the basement surface is sometimes evident from an abrupt change in the areal extent of anomalies, and is marked accordingly.

4. RECOMMENDATIONS

It is desirable that the Bureau secure all available synthetic data concerned with total-magnetic-intensity fields, as a basis for the interpretation of aeromagnetic maps. Some of these data are already in our office and no difficulty should be met in obtaining copies of albums, calculation charts, and polar charts as they are completed.

Certain diagrams of anomalous fields published by Vacquier et al. (1951) require recalculation and redrawing at an enlarged scale to be more useful in comparison with observed anomalies.

Interpretation of aeromagnetic data over sedimentary basins could well be made along the lines suggested in this Record. Estimates of depth to basement rock could be made using depth indices, "express" gradient rules, etc. and the results could be compared with each other and with results of surveys using other geophysical methods.

Development of an electronic computer program for rapid construction of residual maps of magnetic data would provide greater resolution in qualitative interpretation over deep sedimentary basins.

Interpretation of aeromagnetic data could be improved by a study of techniques and case histories in geophysical literature. A list of all literature concerned with magnetic and gravimetric interpretation from 1940 to 1959 has been recently prepared in the Geophysical Branch.

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