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Investigations of Gravitational and Magnetometric Methods of Geophysical Prospecting

By

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CONTENTS

ILLUSTRATIONS

INVESTIGATION OF GRAVITATIONAL AND MAGNETOMETRIC METHODS OF GEOPHYSICAL PROSPECTING

BY

A. H. MILLER

ABSTRACT.—This report is a summary of investigations made with the torsion balance and the magnetometer by the Dominion Observatory. Surveys covered three faults, deposits of asbestos, chromite, pyrite, lignite, siderite, and salt, as well as a buried granite ridge associated with the occurrence of natural gas and oil at Moncton, New Brunswick. Certain of the buried structures were successfuly located and outlined with the instruments. It is concluded that there are probably numerous other instances in Canada where the instruments might be successfully and profitably employed.

INTRODUCTION

Since 1928 the Dominion Observatory has carried on a number of investigations of these methods. For the most part co-operation has been with the Geological Survey of Canada, but surveys were also made in collaboration with the Ontario Research Foundation and the Ontario Department of Mines. Separate reports[1] on several of the individual investigations have already been published and are listed below. Reports on the other investigations appear in appendices of this publication. In addition to discussion of the geophysical results in some detail these reports include as a rule adequate accounts of the geology by some member of the staff of the Geological Survey. It is the main purpose of this report to present a more or less summary account of all the investigations, including a statement of their object, the results obtained, and conclusions reached.

The first geophysical survey in Canada appears to have been made in 1902 by Erik Nyström. This was a survey of nickeliferous deposits with a Tiberg, or Thalén-Tiberg, magnetometer for the Mond Nickel Company. In 1903 the Mines Branch of the Department of the Interior commenced surveys with the magnetometer in connection with an investigation of the iron resources of Canada. Valuable reports containing many excellent maps as well as a text book on magnetometric surveying and the earlier types of magnetometer including the Thalén-Tiberg appear among the publications of that branch up to 1924. In 1922 the first torsion balances (two Hecker balances) were brought to Canada by the Dominion Observatory, but owing to certain fundamental defects in their manufacture no use of the instruments was made until 1929.

By 1928 general interest in geophysical methods of prospecting had been aroused in Canada owing mainly to the introduction of electrical methods which had been applied

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[1] A. H. Miller, C. A. French, and M. E. Wilson. Geophysical Surveys of the Hull-Gloucester and Hazeldean Faults. Memoir 165, Geological Survey of Canada, Part IV, pp. 190–225, 1931.

A.H. Miller. Gravitational and Magnetometric Investigations. Memoir 170, Geol. Surv. Can., Part III, pp. 99–118, 1932. Surveys with the Torsion Balance and the Magnetometer in Eastern Canada. Journal of the Royal Astronomical Society of Canada, Vol. XXVI, pp. 1–16, 1932. Gravitational and Magnetometric Surveys of the Onakawana Lignite and Grand Rapids Siderite Deposits. Canadian Journal of Research, Vol. 10, pp. 463–478, 1934. Dominion Observatory Reprint No. 23.

A. H. Miller and G. W. H. Norman. Gravimetric Survey of the Malagash Salt Deposit, Nova Scotia. Technical Publication No. 737, A.I.M.E., New York, pp. 1–11, 1936. Dom. Obs. Repr. No. 29.

A. H. Miller. Theory and Operation of the Eötvös Torsion Balance. J. Roy. Astron. Can. XXVIII, 1–31, 1934. Dom. Obs. No. 19.

in attempts to locate sulphide ore bodies. By this time considerable areas throughout the country had been surveyed by geophysical prospecting companies. Under the circumstances of their introduction it was natural if not almost inevitable that misunderstanding of the methods should arise. For a number of reasons they were in some quarters actually distrusted. To meet the general demand for authentic and unbiased information, investigation of the methods was begun by the Geological Survey of Canada and the Dominion Observatory in 1928. For the electrical and magnetic methods assistance of the Physics departments of McGill University and the University of Toronto was obtained as well as the willing co-operation of most of the prospecting companies then operating in Canada.

Gravity, terrestrial magnetism, and seismology are branches of the science of geophysics in which the Dominion Observatory has been actively engaged since 1902. Consequently, when investigation of the prospecting methods was contemplated the Observatory had some experimental knowledge of the instruments in use and some acquaintance with the theoretical aspects of the subject.

For the purpose of gaining first-hand information on the use of the torsion balance and field methods of investigation, as well as to compare and report on various types of instruments available, the writer, who was then the physicist in charge of the gravity division, was sent to Europe during the season of 1928. Through the courtesy of the Director of the Geological Survey of Great Britain considerable time was spent with officials of that survey, with the object of becoming familiar with the theory and use of the torsion balance. Visits were made to several other British institutions—to the Geodetic Institute, Potsdam; the Geological Survey of Prussia, Berlin; the Baron Roland Eötvös Institute, Budapest; the Dutch Shell Oil Company, The Hague; and field parties operating in Germany, Hungary, and Scotland.

Following this investigation it was decided in the early part of 1929 to undertake an investigation in this country to ascertain what application the torsion balance might have to geological problems in Canada. Two torsion balances were ordered, one of these being an Askania Z balance, a photographically recording instrument made by the Askania Company of Berlin, the other the latest visual type of apparatus made by Ferdinand Süss of Budapest. Subsequently there were also purchased four Askania magnetometers (two horizontal and two vertical).

Field work was commenced in the autumn of 1929. In 1931 the field program had to be considerably curtailed. Problems which were investigated subsequently to this were undertaken at special request, not because they formed part of a definitely related plan of investigation. Among these, however, were a number of useful investigations, the last one (in 1935) being a survey of a buried pre-Carboniferous ridge associated with the occurrence of natural gas and oil in the vicinity of Moncton.

The primary object of most of the investigations has been concerned with the application of the torsion balance. Owing to the fact that observations with magnetometers did not require much time and added little to the expense, all the ground surveyed with the torsion balance was also partially or completely covered by the magnetometer. Two surveys, Grand Rapids and Moncton, were primarily magnetometric investigations, and at Thetford the work was confined entirely to the magnetometer.

For the most part surveys have been over structures or deposits where the geology was fairly well known from drilling, or where it could be safely inferred from outcrops. In these cases the geophysical methods generally speaking have given results agreeing fairly well with what might be expected from consideration of the geology. In a few cases the surveys were made under circumstances more nearly approaching actual practice; for example, where they were extended from areas of known geology to regions in which the geological relations were uncertain, but nevertheless areas in which some estimate could be made of the possibilities. How well the conclusions from these latter surveys agree with the actual facts cannot as yet be completely answered owing to the lack of drilling tests.

The first three structures selected for investigation were faults, all within a few miles of Ottawa. In acquiring experience with the torsion balance, it was considered desirable to begin with comparatively simple geological structures in areas where the terrain was such that the troublesome topographical corrections did not exceed moderate amounts.

DESCRIPTIONS AND RESULTS OF INDIVIDUAL SURVEYS

1. Hull-Gloucester Fault

Structure.—Normal strike fault, covered by only a few feet of drift, can be traced from outcrops for several miles, estimated throw 1,000 feet, estimated thickness of sedimentary strata on downthrow side 1,400 feet, on upthrow 400 feet, basement Precambrian (Fig. 1).

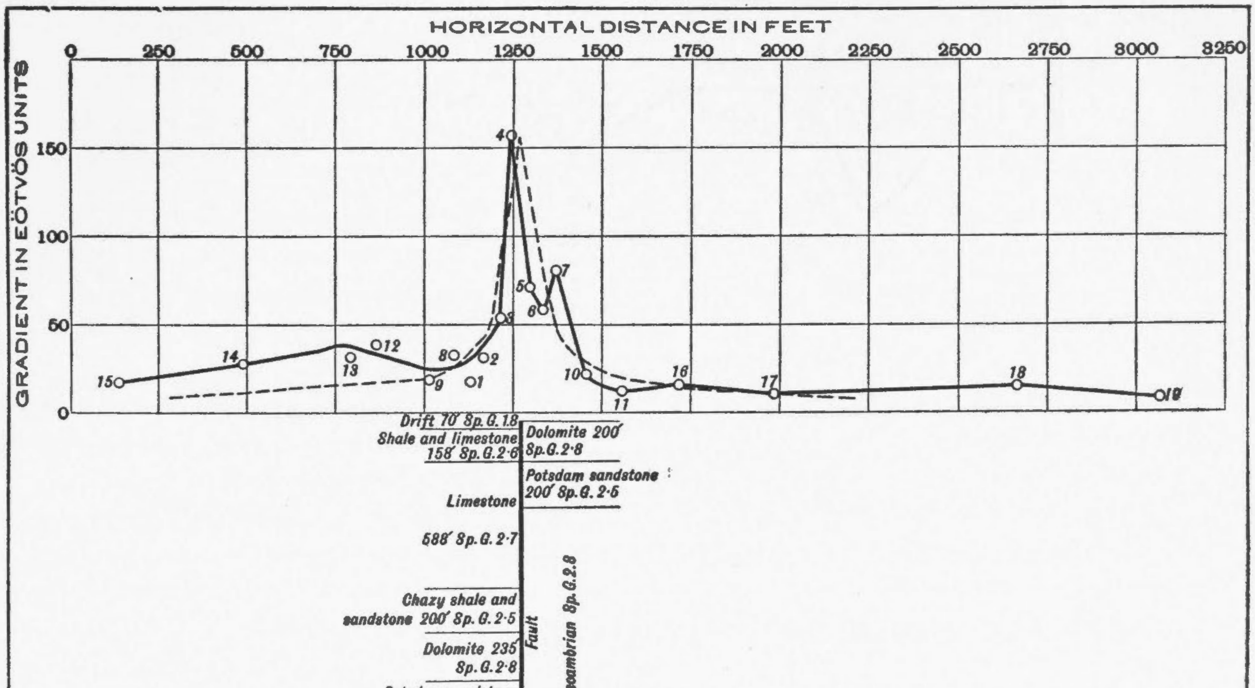

Fig. 1.—Gradient graph, Hull-Gloucester fault at Leitrim, Ontario. Theoretical values for the assumed geological section are represented by the broken line, observed values by the continuous line.

Topography.—Flat to gently sloping, two or three knolls.

Instruments employed.—Two torsion balances, one magnetometer–earth-inductor, and one Dover dip circle.

Extent and date of survey.—About 85 acres were covered in 1929 and 1930 with 70 torsion balance and 29 magnetic stations.

Results.—*(a) Torsion balance:* The course of the fault was traced with precision for a distance of about one-half mile to the limits of the survey. Reasonable estimates were made of the depth of the cover and the throw of the fault. By comparison of computed curves with observed gradient and curvature graphs, the density of the Precambrian was estimated to be 2·8. The gradients and curvatures were equally useful in the general interpretation of results.

(b) Magnetometer: No very marked nor definite effects were observed, probably indicating that the Precambrian rocks in this part of the structure are only slightly magnetic.

2. HAZELDEAN FAULT (A)

Structure.—Normal fault, drift cover 20 to 50 feet, can be traced from outcrops for several miles, throw probably about 500 feet, estimated thickness of sedimentary rocks in downthrow 700 feet, in upthrow 200 feet, basement Precambrian, Strike N 65° W magnetic (Fig. 2).

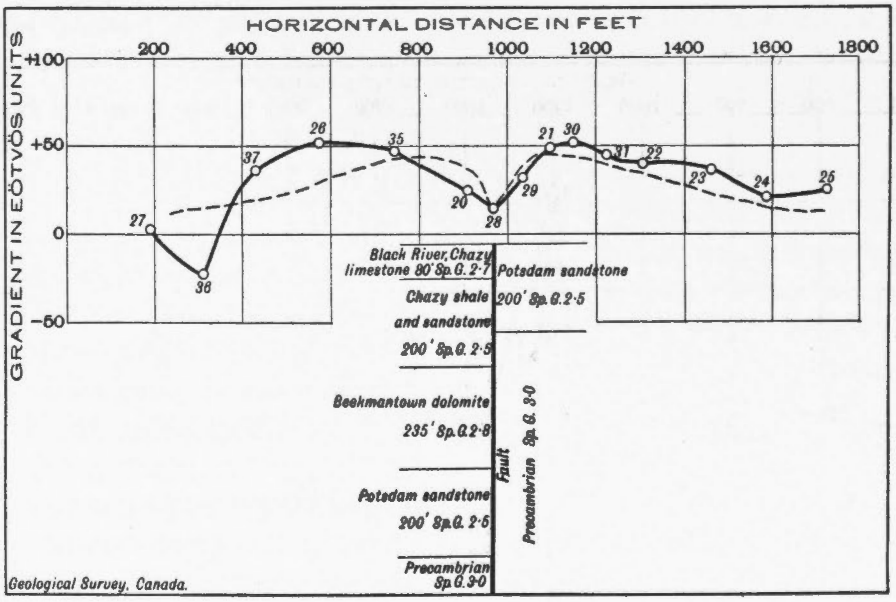

FIG. 2.—Gradient graph—Hazeldean fault, Hazeldean, Ontario. Theoretical values for the assumed geological section are represented by the broken line, observed values by the continuous line.

Topography.—Slopes up to 5 degrees. A few knolls.

Instruments.—Same as in survey 1.

Extent and date of survey.—Approximately 90 acres were covered in 1929 with 46 torsion balance and 64 magnetic stations.

Results.—(a) Torsion balance: The results were in this case not so uniform as for survey 1. On the whole the gradients were in good agreement with the geology. The course of the fault was traced for about 2,000 feet along the strike to the limits of the survey, by the line of minimum gradients. The fault could also be traced from the curvatures but not so closely or so satisfactorily as with the gradients, as it was only on one side of the fault plane that consistent regularity in the curvatures was observed. The density of the Precambrian was estimated at 3·0.

(b) Magnetometer: The three torsion balance traverses were followed. The maximum in the horizontal intensity along these served to trace the fault almost as accurately as the torsion balance. From the anomalies in the vertical magnetic intensity it was also possible to follow roughly the course of the fault through the area covered by the observations.

3. HAZELDEAN FAULT (B)

Structure.—The same fault as in the previous case about 3 miles along the strike to the northwest, drift cover fifty feet or more; strike N 45° W magnetic. The course of the fault across the area of the geophysical survey could be inferred from outcrops near the limits of the area. In the upthrow, sedimentary formations are, here, probably entirely absent, or present in the form of a very thin layer of sandstone only. The estimated throw is about 500 feet corresponding to the probable thickness of sedimentary strata in the downthrow.

Topography.—Over most of the area slopes did not as a rule exceed two to three degrees. There were some topographical features up to 50 feet or more above the general level near the limits of the survey on the upthrow side.

Instruments.—Two torsion balances, and two vertical magnetometers.

Extent and date of survey.—Approximately 230 acres were covered in 1930 with 79 torsion balance and 102 magnetic stations.

Results.—(a) Torsion balance: The course of the fault was traced for a distance of over half a mile entirely across the area surveyed by the line of maximum gradients and also somewhat more definitely and satisfactorily by the 90-degree change in the curvature (Fig. 3). From the magnitude and the distances of the maximum and minimum curvatures from the fault plane, it was estimated that the Precambrian exceeded the density of the sedimentary strata by at least 0·3, that the drift cover was greater than 59 feet, and the thickness of the sedimentary strata less than 1,500 feet. This is a good estimate of the drift, but the figure for the sedimentary strata is probably at least twice the actual thickness. The results appear also to give a good indication of the nature of the buried rock topography on either side of the fault.

(b) Magnetometer: The line of maximum vertical intensity roughly paralleled the course of the fault across the area surveyed, being as a rule from 100 to 150 feet from the fault plane on the upthrow side. Anaylsis of the results indicated that the magnetization of the structure was in general induced by the earth's magnetic field and that the observed intensity curve for the main traverse was similar in form to that which would result from uniform magnetization. On this assumption a quite plausible value was obtained for the magnetic susceptibility of the Precambrian. Both positive and

negative anomalies larger than any found along the fault line were discovered in one region within about 1,000 feet of the fault on the upthrow side.

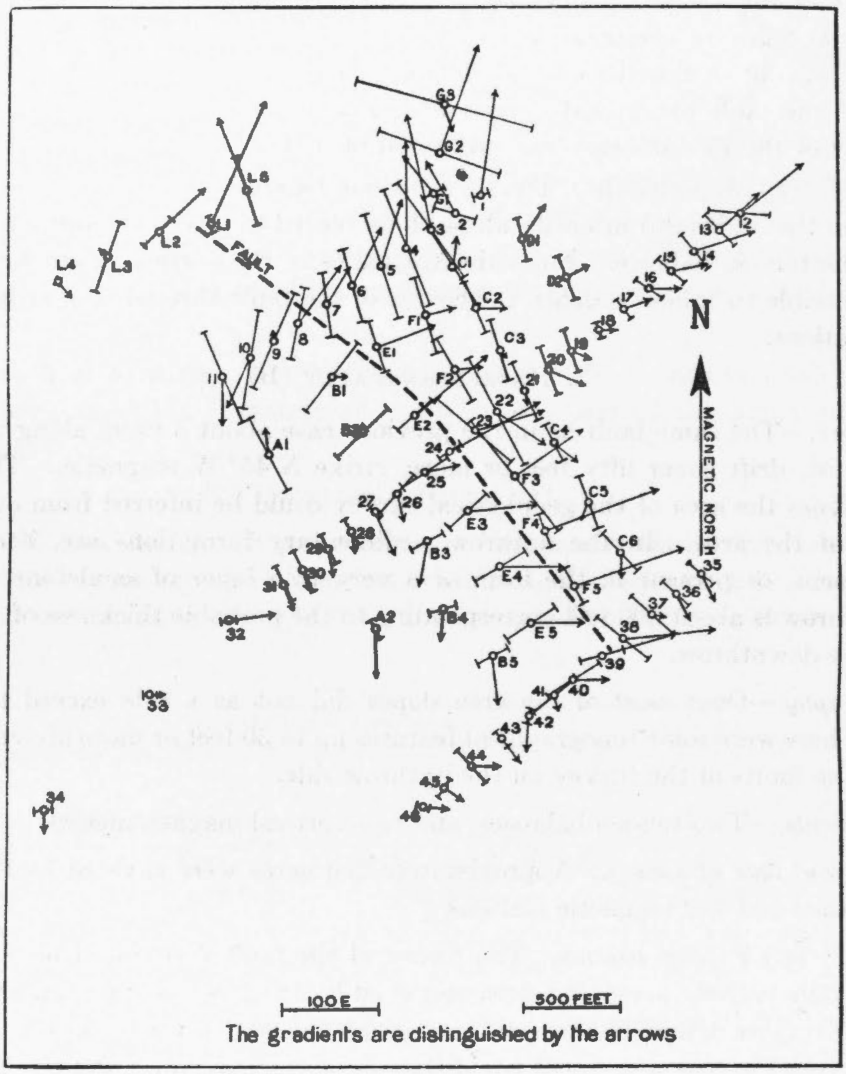

FIG. 3.—Gradients and curvatures—Hazeldean fault, Hazeldean, Ontario.

4. ASBESTOS AND CHROMITE DEPOSITS, IN SERPENTINE BELT, NEAR THETFORD, QUEBEC.

Structure.—Geology and structural relations have been described by H. C. Cooke[3] who has also given a résumé of the geophysical results. The deposits occur in intrusions of basic igneous rocks consisting of dunites and peridotites, now largely altered to serpentine, together with some associated gabbro and pyroxenite, and small amounts of granite and allied rocks. They are intruded into sediments consisting for the most part of slates, quartzites, schists, and some basaltic lavas. Studies of the chemical and mineralogical nature of the chromites were made by E. Poitevin (No. 2288[2]).

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[3] Geol. Surv. Can. Pub. No. 2288, 2306, 2330 (Summ. Reports—Parts D for 1930, 1931, and 1932), and No. 2440, Memoir 211, 1937.

Object of investigation.—To determine the value of the magnetometer in locating chromite and asbestos.

Instruments.—Vertical, and horizontal magnetometers; Hotchkiss superdip; Gurley dip needle; Brunton compass; and 5-inch Cooke transit.

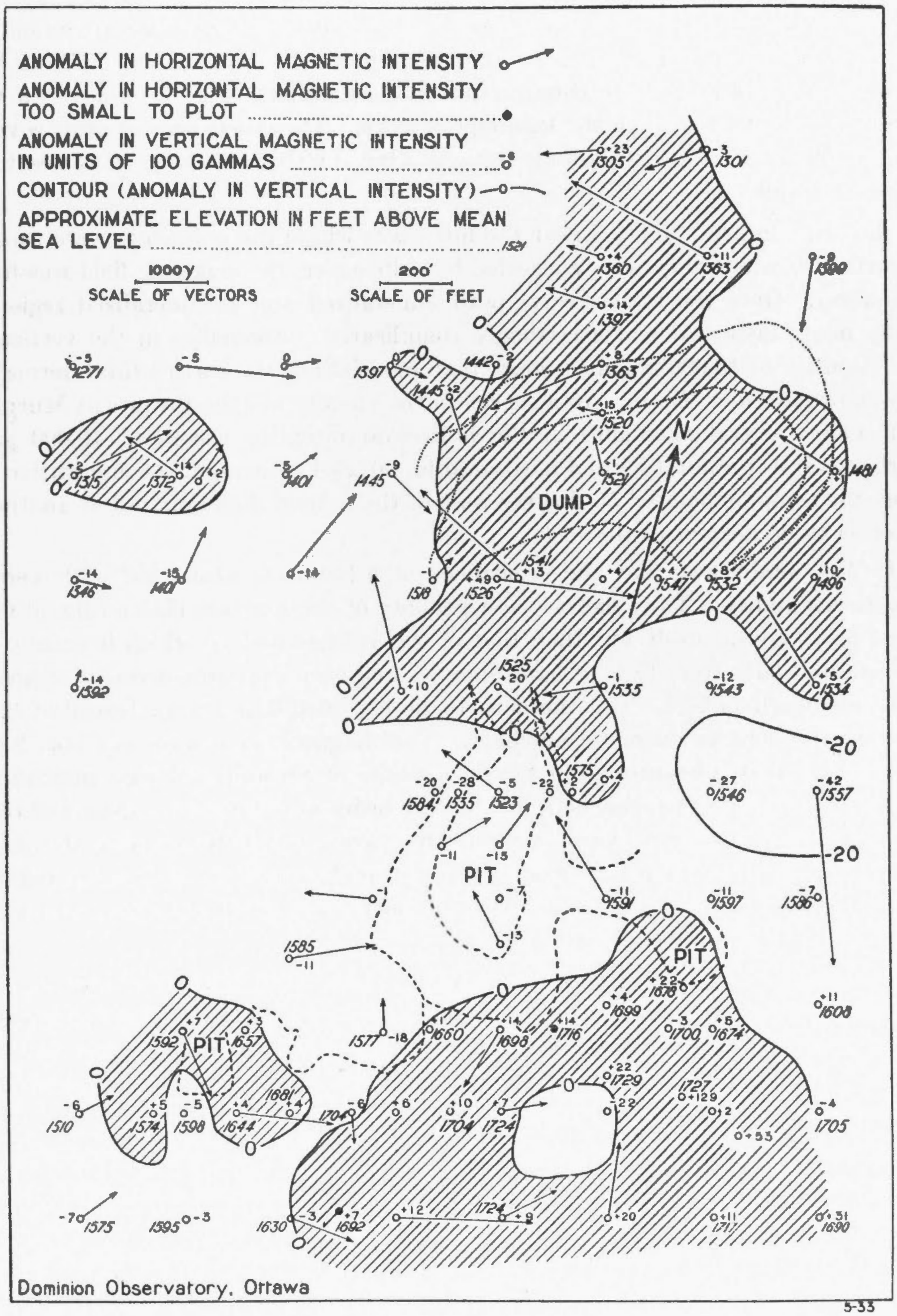

Fig. 4.—Magnetic anomalies—vicinity of asbestos pits at Murphy hill, Black Lake, Quebec.

Date and extent of survey.—During the seasons of 1930, 1931, and 1932 approximately 900 stations were established within the limits of the main serpentine body in the vicinity of Thetford Mines, Black Lake, Caribou lake, Red hills, and Vimy Ridge mine, and also at several points along the Pennington dyke, and dykes near West Broughton. Measurement of the declination was made at about 300 of these stations, and of the anomaly in the horizontal intensity at about 500. Observations were spread out in the form of networks at three places in the vicinity of (a) asbestos pits on Murphy hill, Black Lake (Fig. 4 and 5), (b) chromite pits at Caribou lake (Fig. 6), and (c) the Quebec Asbestos property (Fig. 7) in the Pennington dyke. These networks or grids covered an area of 250 acres. The remaining stations were distributed along traverses totalling altogether 9 miles.

Results.—In areas not too near the intrusives where the sediments were exposed at the surface or where they were concealed by drift cover, the magnetic field was found to be uniform. Over the intrusives in both mineralized and unmineralized regions it is usually much disturbed and exceedingly complicated. Anomalies in the vertical magnetic intensity of 10,000 gammas (more than one-sixth of the earth's total normal force) are by no means uncommon. In a survey in the vicinity of asbestos pits at Murphy hill, Black Lake, several anomalies in the horizontal intensity exceeding 10,000 gammas (nearly equal to the total normal horizontal force) were measured. At one station in this survey the compass pointed 55 degrees west of the normal direction and at another only 25 feet away 65 degrees to the east.

It was established that the occurrence of asbestos is associated with very large magnetic anomalies. The magnetic susceptibility of chromite ore is as a rule (at Caribou lake at least) considerably less than that of the average rock in which it occurs. This was indicated both from tests of hand samples and also from measurement of anomalies at pits near Caribou lake. It is therefore to be expected that a large deposit of chromite would give a definite magnetic anomaly. The magnetic anomalies are not, however, confined to asbestos bearing rocks nor to deposits of chromite. Large anomalies were observed within the serpentine belt, in what are believed to be barren areas well removed from ore deposits. Specimens of rocks in these areas, when tested with the magnetometer, were found to be highly magnetic, as strongly magnetic as samples taken from the asbestos pits. One of the most strongly magnetized of all specimens was a sample obtained in one of these supposedly barren areas.

A map depicting the magnetic anomalies over the entire serpentine belt would need to be drawn on a very large scale to include a fair proportion of even the larger ones. Judging from the measurements that have been made, it would be a most complicated pattern. The probability of any particular anomaly being due to or associated with the occurrence of either chromite or asbestos would certainly not be large.

In several traverses of Pennington dyke and dykes near west Broughton it was usually possible to locate the contacts between the sediments and the intrusive from the magnetic results. This was also possible in case of the single traverse crossing a contact with the main body (Fig. 8). In some of the dyke traverses, no definite indication of the contacts was obtained. This occurred in cases where the peridotite was altered to soapstone or where the peridotite approached the form of soapstone. In one survey

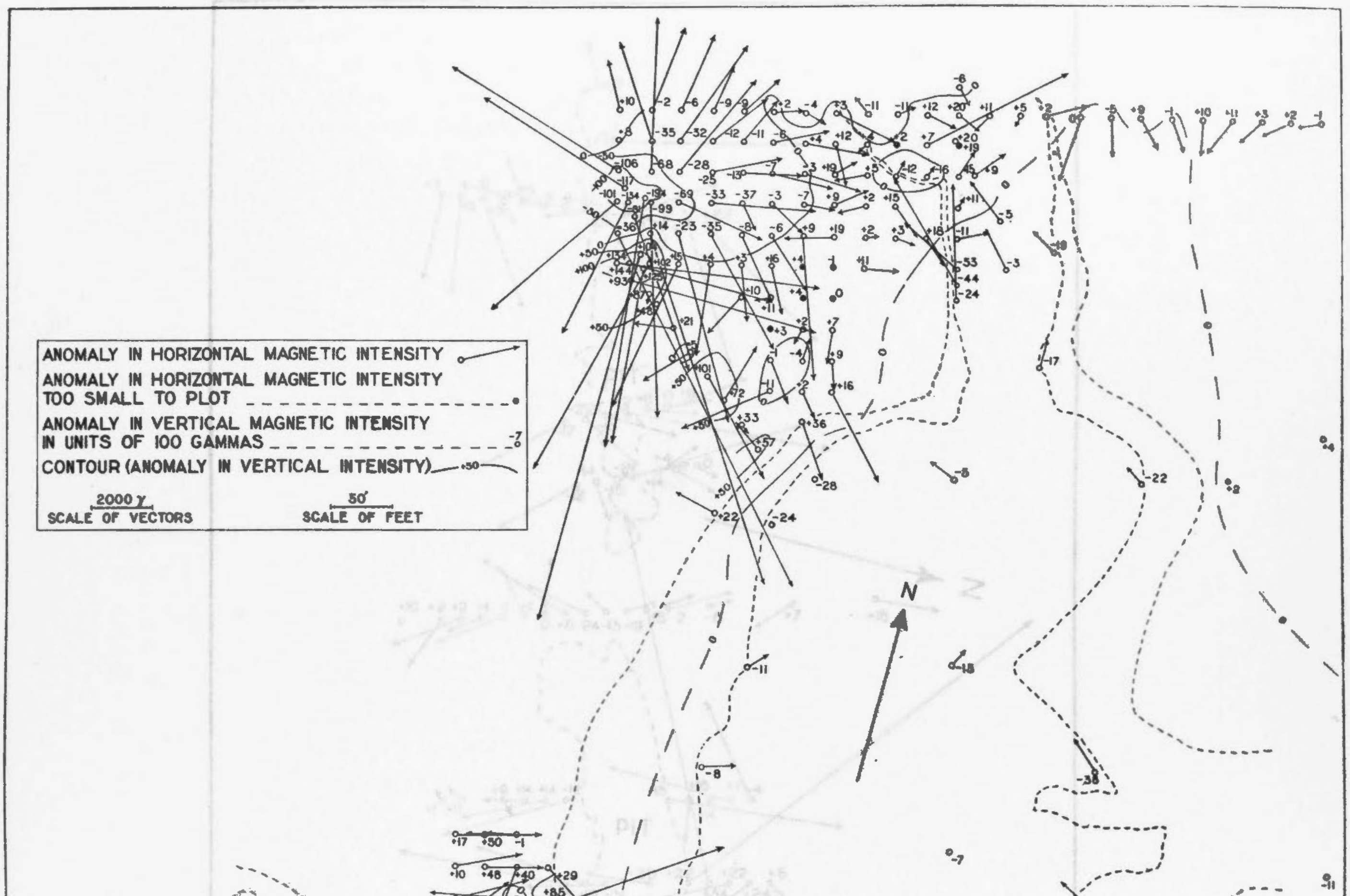

FIG. 5.—Magnetic anomalies—Murphy hill, Black Lake, Quebec. Two intense magnetic poles of opposite sign to the northwest of main asbestos pit. North pole ($-19{,}400\gamma$) at top centre of figure, south pole ($+14{,}400\ \gamma$) 55 feet south.

[illegible] seasons of 1930, 1931, and 1932 approximately [illegible] main serpentine body in the [illegible] lake, Red hills, and Vimy Ridge mine, [illegible] dyke, and dykes near West Broughton. [illegible] about 600 of these stations, and of the [illegible] Observations were spread out in the [illegible] of (a) asbestos pits on Murphy hill, Black Lake [illegible] pits at Caribou lake (Fig. 6), and (c) the Quebec Asbestos [illegible] These networks or grids covered an area of [illegible] acres. The remaining stations were distributed along traverses totalling altogether [illegible] miles.

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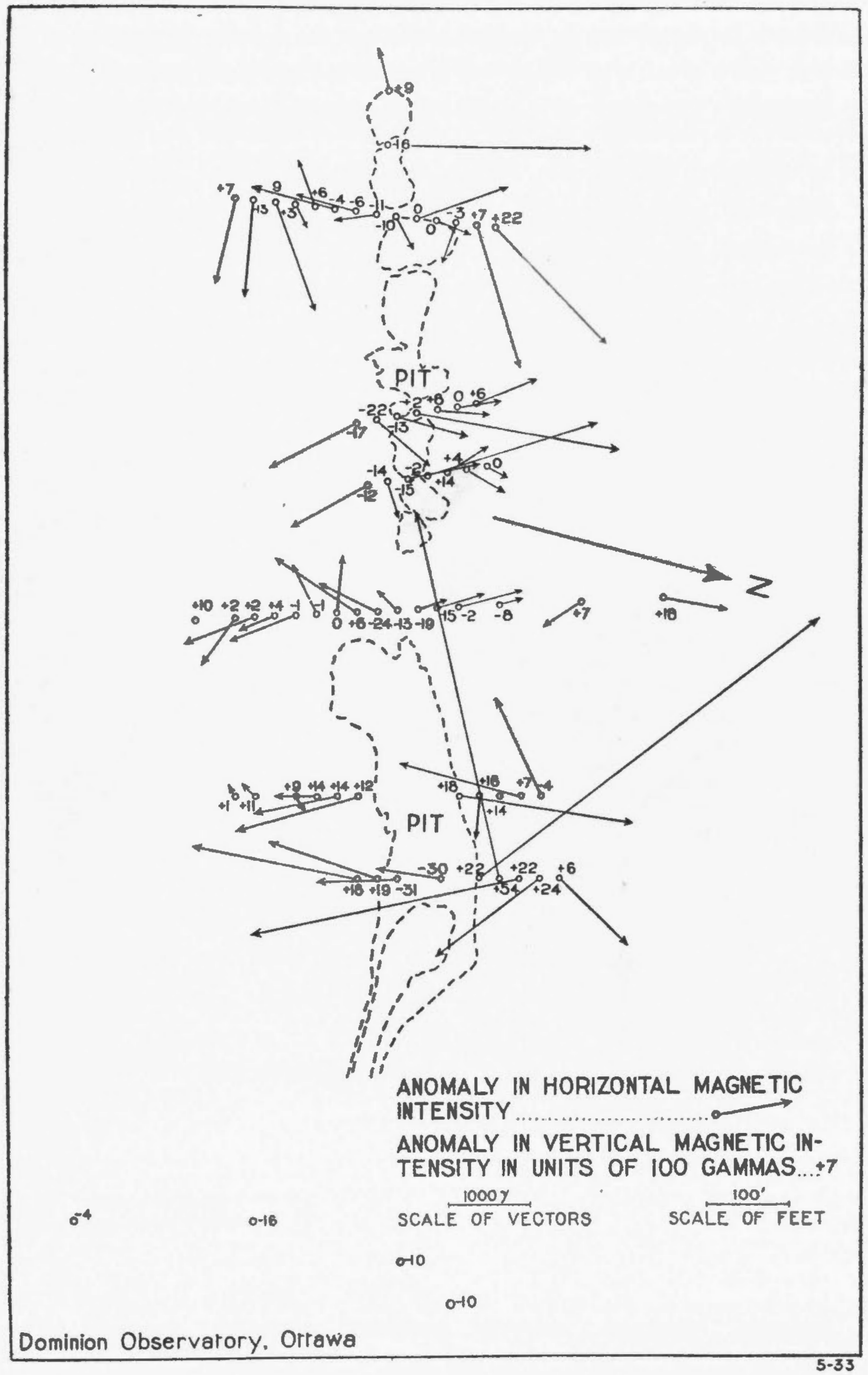

FIG. 6.—Magnetic anomalies—vicinity of chromite pits, Caribou lake, Quebec.

within Pennington dyke an area of asbestos bearing peridotite could be distinguished by the anomalies from adjacent areas of non-asbestos bearing peridotite (approaching soapstone in places) and of soapstone. It was evident that in this case both the soapstone and the latter form of peridotite were, like the sediments, comparatively non-magnetic.

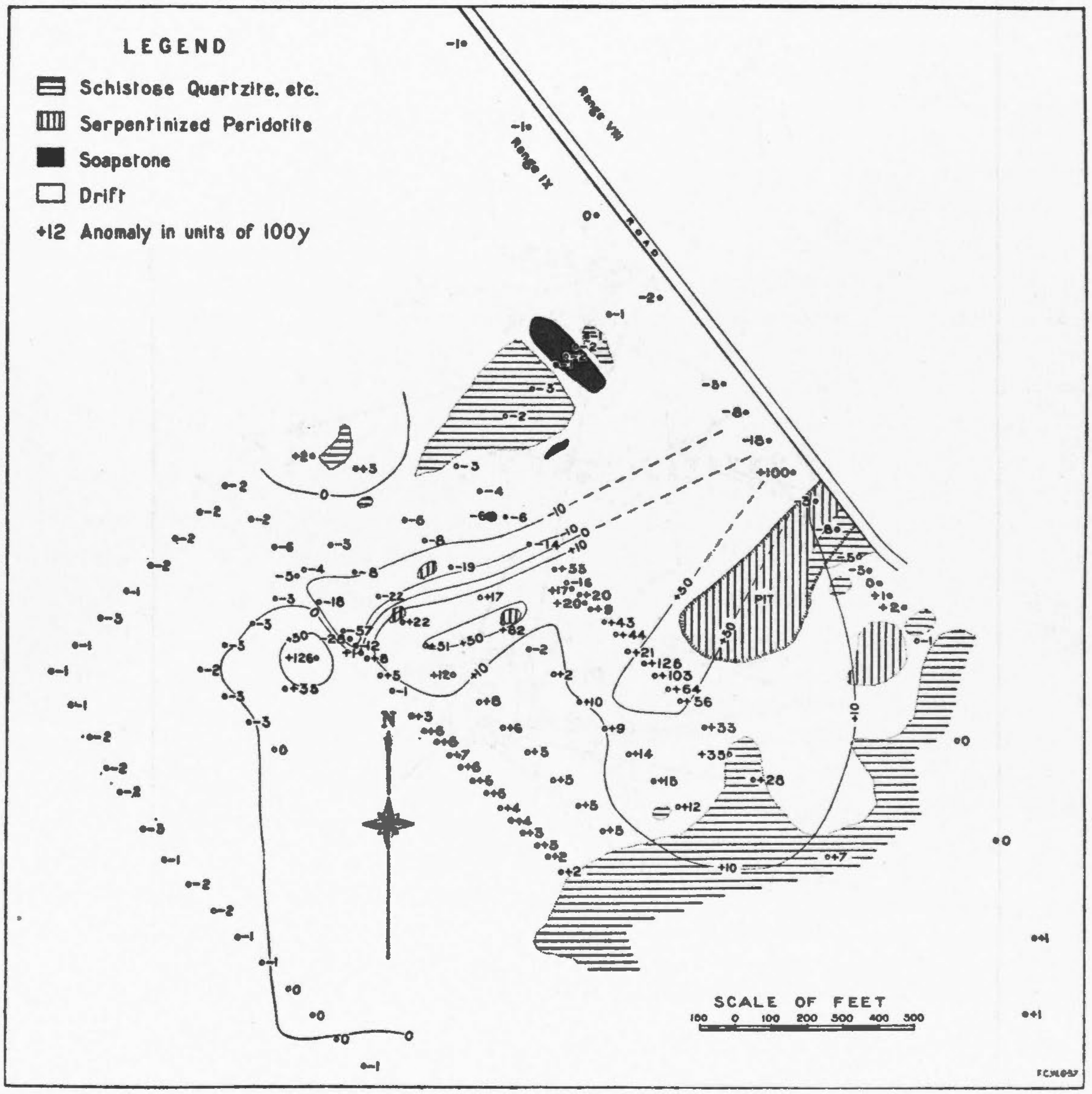

Fig.—7.—Anomalies in vertical magnetic intensity, Quebec asbestos property, lots 12 and 13, range IX, Broughton township, Quebec.

In view of the complicated nature of the magnetic field within the intrusive, the magnetometer can hardly be of much or any value in the direct location of asbestos or chromite. Indirectly it may have a limited application in outlining the rock formation in which these minerals are likely to occur. In the survey of the Quebec Asbestos property (Fig. 7), the location of the serpentinized peridotite is indicated over a considerable area.

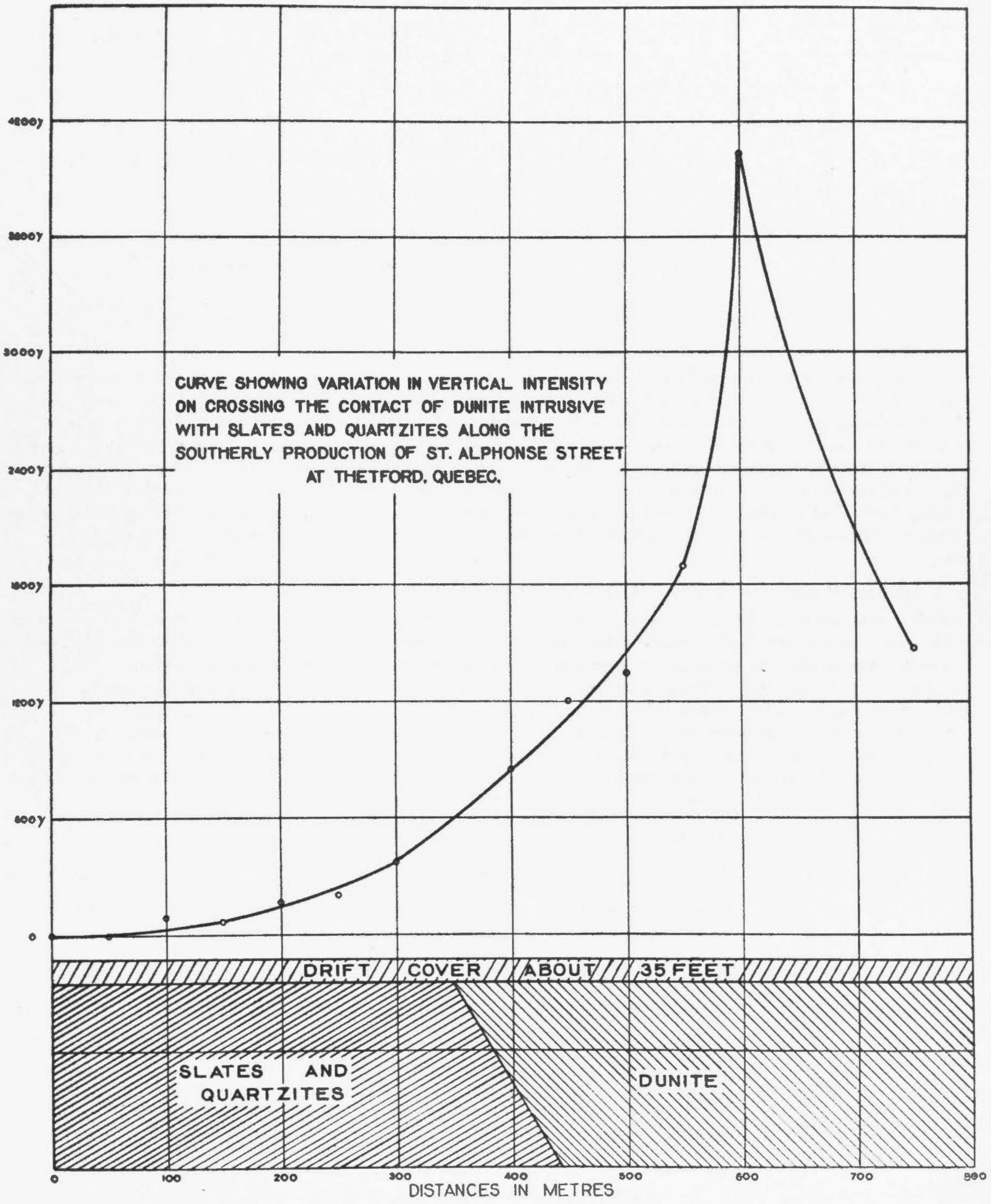

FIG. 8.—Variation in vertical magnetic intensity at contact of serpentine belt with slates and quartzites, Thetford, Quebec.

Throughout the whole area the larger anomalies are so great that they produce large deflections on the dip needle and the compass. The strong magnetic poles* frequently observed within the main serpentine belt are easily outlined with the dip needle. Three traverses were made of Pennington dyke with dip needle and Brunton compass. Along one of these traverses, the drift cover may have been as much as 50 feet. Deflections of over 20 degrees on the dip needle and 5 degrees on the compass were produced. The contacts could be located about as accurately with the dip needle as with the more sensitive instruments.

5. CALDWELL PYRITE DEPOSIT, RENFREW COUNTY, ONTARIO

Structure.—Geology and structural relations have been described by M. E. Wilson[3] as follows:

> "The pyrite ore consists partly of pyrite associated with quartz and calcite and partly of pyrite mingled with various proportions of hornblende or hornblende-biotite schist that forms the country rock. The ore of the first type has the appearance of a breccia, the pyrite occurring as broken fragments enclosed in a matrix of quartz or of quartz and calcite; and it is owing to this relationship of the pyrite and quartz that where the ore outcrops at the surface the quartz from which the pyrite has been weathered away has a honeycomb or sponge-like appearance. The ore of the second type is merely a phase of hornblende schist in which pyrite is included in all proportions, ranging from schist in which the pyrite is sparsely disseminated or present in small aggregates extending along the planes of foliation to ore in which the schist is present in only scattered masses throughout thicknesses of several feet."

In Fig. 9 and 10 there is indicated as ore that

> "which in practice would be mined either for shipment as taken from the mine or for shipment after concentration in the mill. In addition to the quartz, calcite, and pyrite composing the ore, the only other mineral observed to be present was pyrrhotite, which occurs here and there in the ore but is not an abundant constituent. The relationship of the ore and the enclosing hornblende-biotite schist is most indefinite, the ore generally passing into the schist transitionally. The deposits appear to have in the main an approximately lenticular form and trend parallel to the foliation of the enclosing schist. The strike of the foliation and banding in the schist varies greatly from point to point, but in the main trends approximately north 75 degrees west, magnetic. The dip of the foliation and banding on the average is approximately 60 degrees to the northwestward. The pyrite deposits are not distributed in alignment with one another but in parallel or echelon arrangement."

(as indicated by the sections at the lower level in Fig. 9 and 10).

Measurement of the density of eight samples of the country rock gave an average value of 2·94 with a range of 0·20. A pure specimen of the ore had a density of 4·62. The average ore density is no doubt somewhat less than this.

Object of investigation.—This property was selected for investigation partly on account of the comparatively rough topography of the area in which the deposit lies. It was realized that the terrain corrections which would have to be applied to the observed torsion balance results on account of the broken topography would be very large and subject to considerable error in evaluation. Would the finally corrected values be of any use in outlining the position of the heavy ore deposit?

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* The difference in the dip needle readings at the two magnetic poles (S and N) to the northwest of the main asbestos pit (Fig. 5) was 110 degrees, corresponding to an average sensitivity of about 300 gammas per degree deflection. The south pole (positive anomaly 14,400 gammas) is 55 feet approximately magnetic south of the north pole (anomaly 19,400 gammas). The ground elevation at the north pole is 15 feet lower than at the south pole. Throughout the entire area five anomalies exceeding 13,000 gammas in the vertical intensity were measured. Of these four were positive and one negative. The largest anomaly was +23,000 gammas, in the Red Hills (pyroxenite) area.

[3] Geol. Surv. Can. Pub. No. 1820, pp. 30–35 (Summ. Rept., 1919, Part E).

Topography.—On the southern side of the ore body the topography is not so rough, but on the northern side slopes of 20 degrees or more are not uncommon. The difference in elevation between a station over the ore body and the most northerly station, distant 1,000 feet, was 250 feet. Levels were taken to a distance of 30 metres from each station for the purpose of computing the terrain correction. A contour sketch was compiled from the terrain levelling, and from barometric readings and an existing topographical map of part of the area. Topographical corrections to the gradient were computed from this sketch for a distance of 400 metres from each station. A further correction, an important one in this case, was made for the rock topography beneath the drift. At most stations the covering was shallow and could be determined by sounding with a thin steel rod, the soundings being made in the four cardinal directions to a distance of 10 metres.

Instruments.—Two torsion balances, and one vertical magnetometer.

Date and extent of survey.—The survey was made in 1930. Approximately 30 acres were covered with 47 torsion-balance stations. This area included the only three ore masses (Fig. 9 and 10) that have so far been revealed by the drilling and mining operations. Approximately 150 acres were covered with 215 magnetometer stations. This latter area included the three ore masses previously mentioned and every outcrop in the vicinity of the mine except one.

Results.—*(a) Torsion balance:* A few observations with the torsion balance were sufficient to demonstrate an effect evidently due to the existence of the ore. However, even after the results had been carefully corrected for both surface and subterranean topography (rock surface beneath drift), the plotted values showed no very obvious relation to the ore bodies. Nevertheless it was apparent that they were being influenced by the existence of the deposits and furthermore that most of the gradients were subject to a persistent regional influence. Taking the average for all stations it was found that the regional effect amounted to 58 Eötvös units in a direction 28 degrees east of magnetic north or nearly at right angles to the foliation of the country rock. Some such regional anomaly is to be expected from the general geological relations. The pyrite deposits occur in a belt of heavy rock several miles in width, consisting of gabbro, hornblende or hornblende biotite schist. About one mile west of the deposits, contact occurs with a broad belt of lighter rocks consisting of fine pink to grey aplitic gneiss with which a considerable proportion of pegmatite is associated. The trend of both belts is northwesterly. If the direction of the contact were exactly northwest, it would give rise to a gradient directed northeast or only about 25 degrees to the east of the observed regional effect. Increase in the density of the hornblende to the northeast is also to be anticipated, as, within the zone from the deposits to the contact already mentioned, the hornblende schist has been injected parallel to the formation with granite. It is also possible that part of the regional anomaly may be accounted for by error in the topographical correction. After the gradients had been finally corrected for this regional effect, it was evident (Fig. 9) that they were closely related to the occurrence of the ore. The resulting isogams give a good indication as to where the bulk of the ore is concentrated. From the asymmetry of the gradient profile, across the main ore mass (No. 2), the dip of the ore body was estimated at 65 degrees, agreeing almost exactly with the actual inclination.

(b) Magnetometer: Although the magnetic intensity was by no means uniform over the area covered by the magnetometer, it was only in the vicinity of the deposits or outcrops that large anomalies occurred. The trend of the large positive anomalies follows that of the outcrops and the deposits (Fig. 10). Continuation of the pyrite to the east of the prospected area is indicated by the magnetometer. This easterly section was not covered with the torsion balance. Deflections of the magnetometer produced by a few hand samples indicated that the anomalies are not due to the pyrite itself (at least the better grade) but apparently to closely associated rock, test samples of which might have included some of the disseminated type of ore.

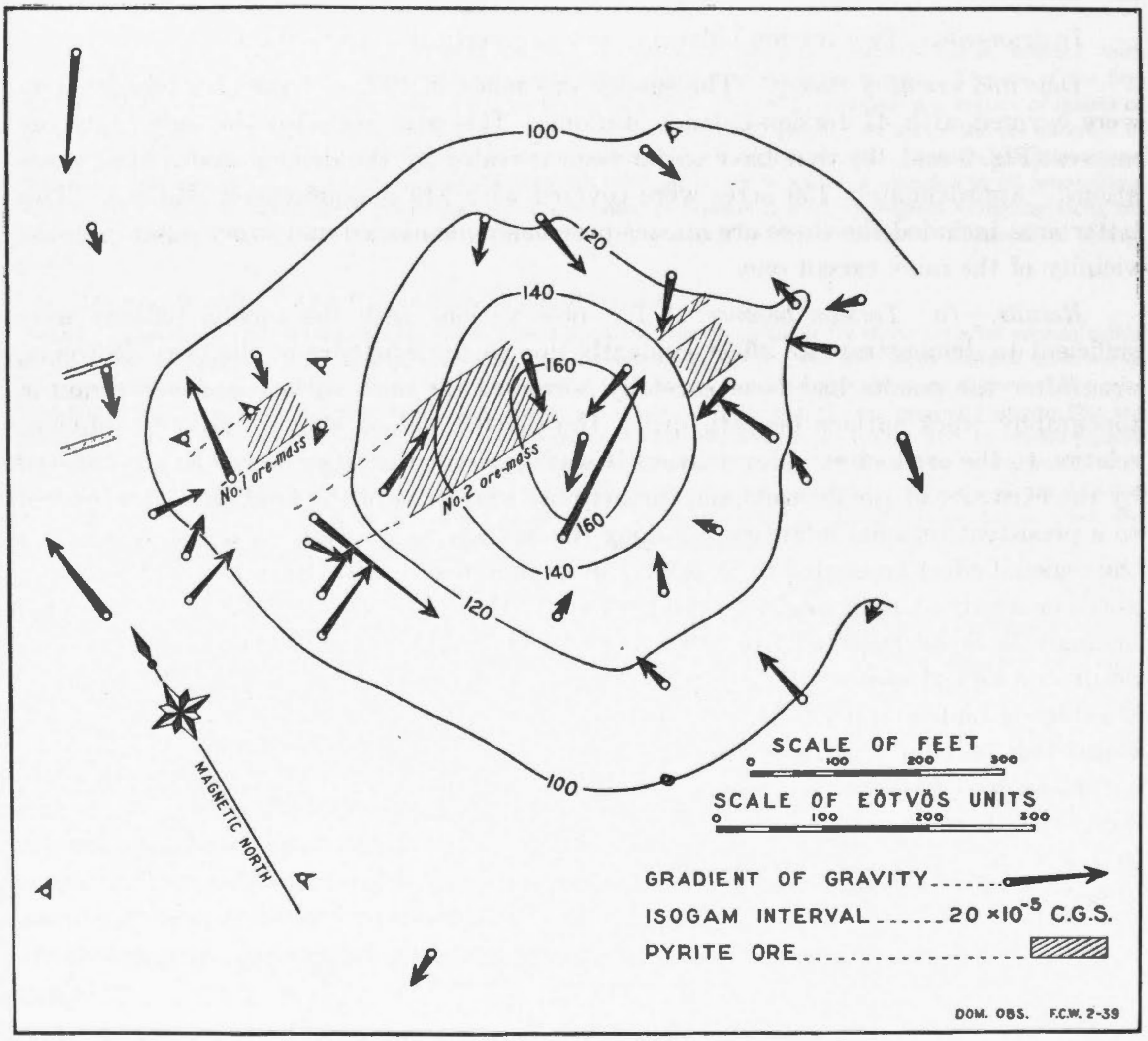

FIG. 9.—Gradients and isogams in relation to ore at depth of 190 feet below head of shaft 2, Caldwell pyrite deposit, Renfrew county, Ontario.

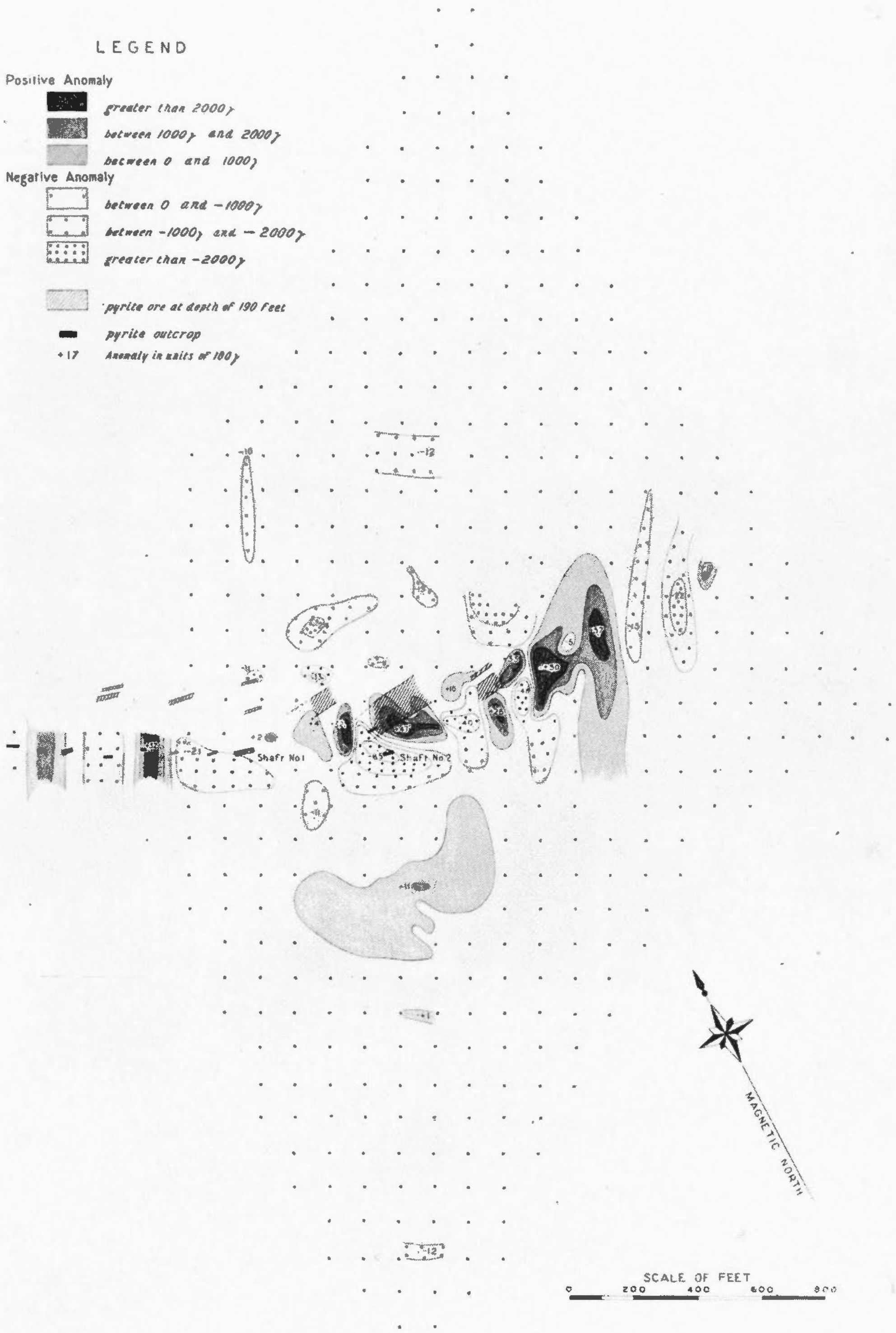

FIG. 10.—Anomalies in vertical magnetic intensity—Caldwell pyrite deposit, Renfrew county, Ontario.

6. ONAKAWANA LIGNITE DEPOSIT, MOOSE RIVER BASIN, ONTARIO

Structure.—The geology and structure of the Onakawana lignite field has been described by W. S. Dyer[4]. The Pleistocene and Cretaceous, with which we are chiefly concerned in the geophysical surveys, have been fully described by Dyer and Crozier.[5] An idea of the structural relations may be gathered from Fig. 11. The lignite occurs in Cretaceous clay overlain by 50 to 150 feet of boulder clay. The boulder clay is in turn overlain by a layer 10 feet thick (not shown on Fig. 11) of marine clay, on top of which at the surface is a layer of about 4 feet of muskeg. As a rule, both the marine clay and the muskeg preserve almost constant thickness.

The densities are as follows: lignite 1·2, Cretaceous clay 2·0, boulder clay 2·3, marine clay 2·0, muskeg 0·2 increasing with depth—average for muskeg about 0·7.

Object of investigation.—Undertaken at the request of the Ontario Research Foundation to determine the possible application of the torsion balance to the location of such lignite deposits.

Topography.—Except quite close to the rivers, the surface is very flat. As a rule, terrain corrections are negligible, or can easily be made so with little preparation of the torsion balance station.

Instruments.—Torsion balance (photographically recording), and vertical magnetometer.

Date and extent of survey.—The survey was carried out in 1931 in co-operation with the Research Foundation and the Ontario Department of Mines. More than 4 miles of traverse, across three lignite seams, were covered with 79 torsion balance stations at intervals of 100 metres. Eighty-two observations were taken by R. H. Hawkins with a vertical magnetometer in the northwesterly part of the lignite field.

Results.—*(a) Torsion balance:* The most important result obtained is illustrated by Fig. 11. Where the lignite seams are thick gravity is low. Bore holes, in any of the three pronounced gravity lows, would strike lignite. Fair estimates of the thickness of the seams can be made from the gravity differences. Although it must be borne in mind that the chances of striking lignite at any point along this traverse, apart from all other considerations, are about 6 to 1, there is nevertheless definite indication that the torsion balance would be of some value in locating lignite.

(b) Magnetometer: A range in magnetic intensity of 300 gammas was observed. The anomalies maintain uniform values over large areas. The extreme northeasterly part of the lignite field (subdivisions A1 and B1 of Dyer and Crozier) is characterized by positive anomalies, while the remainder of the area observed by Hawkins is negative. The cause of these anomalies is not known. They do not appear to be related to the thickness of either the lignite or the boulder clay. It is also doubtful if they are related to even the nature of the boulder clay. In view of the regional tendency, they may be due to more deep-seated causes.

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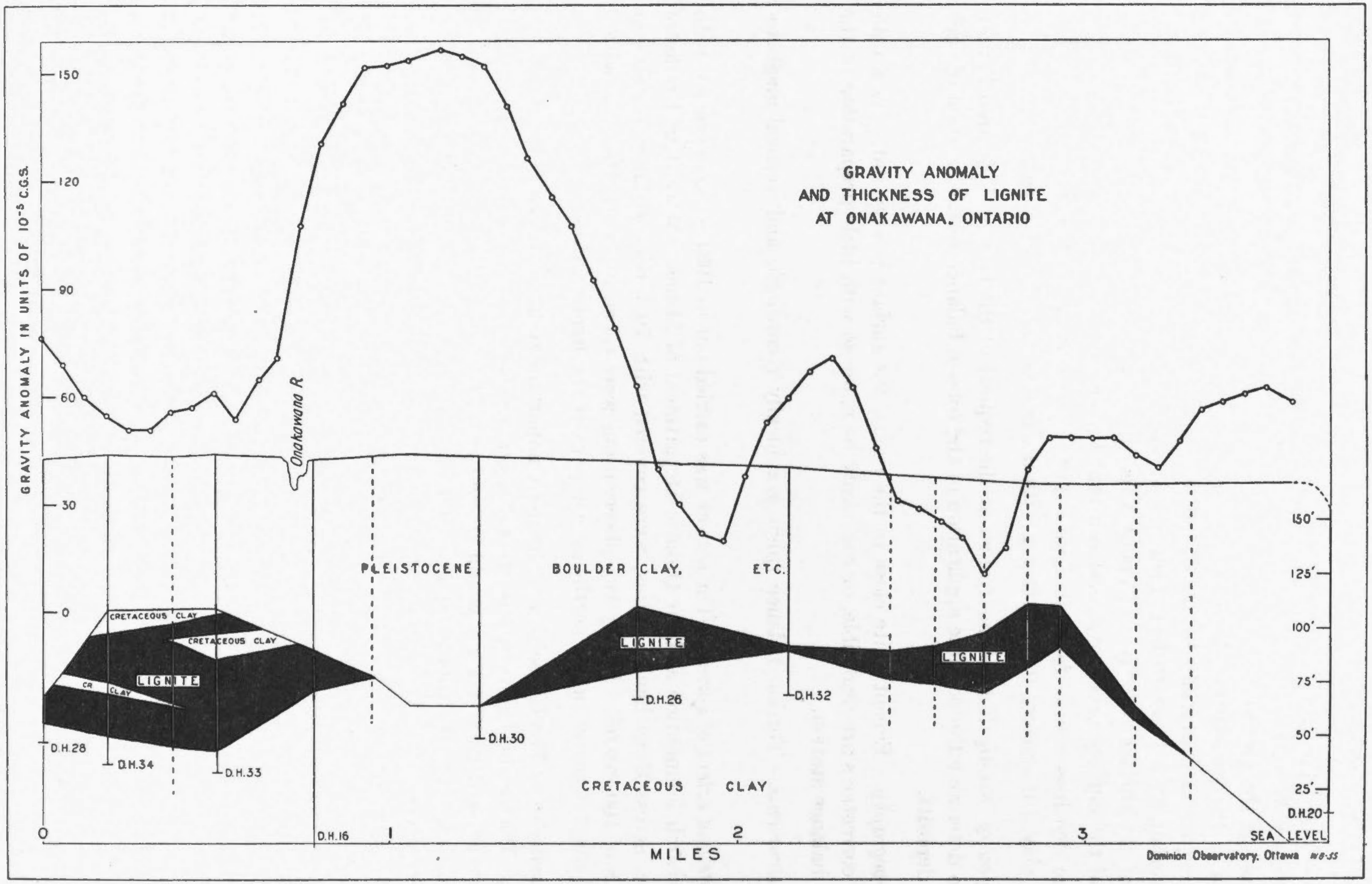
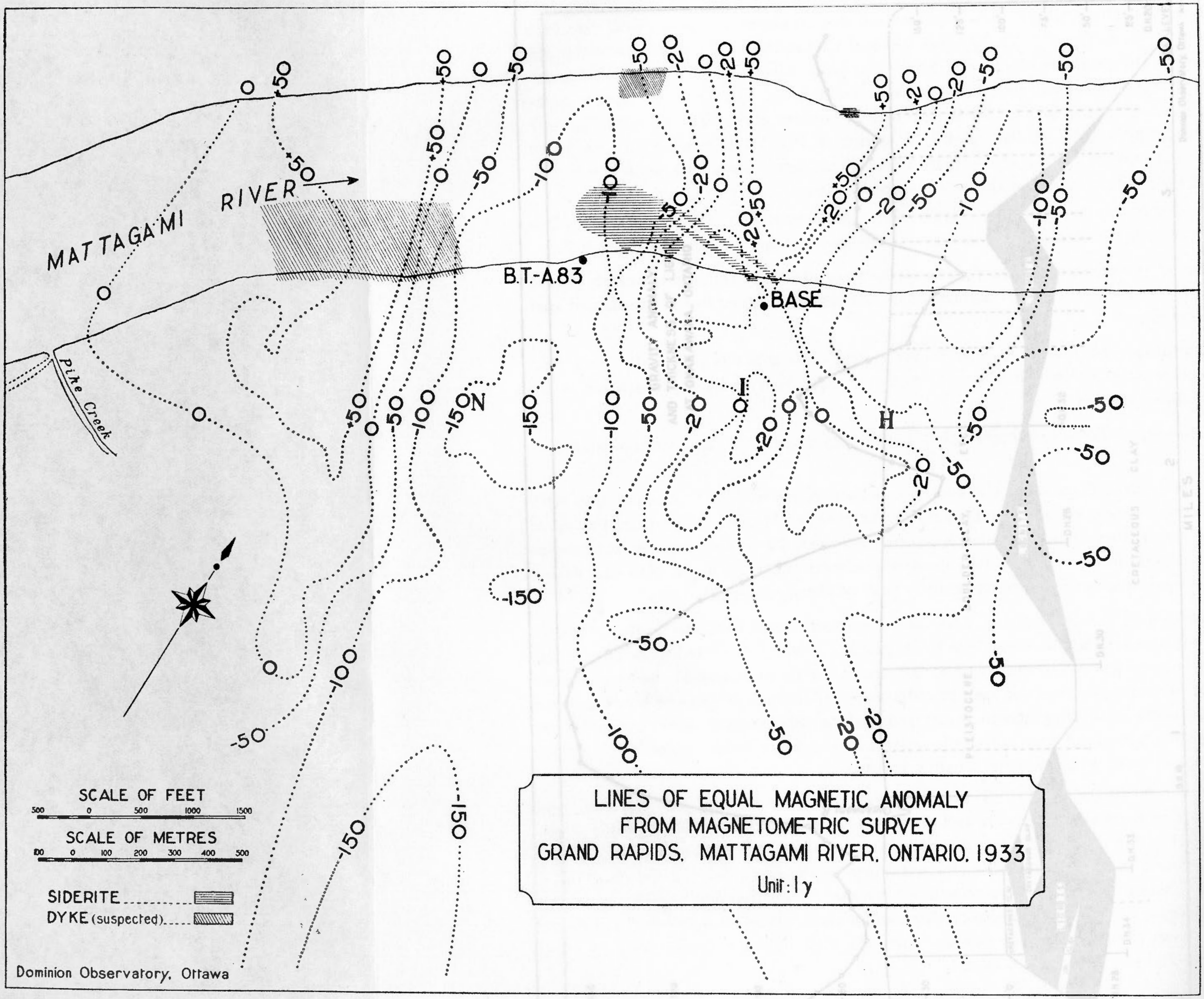
[4] Trans. Roy. Soc. Can., 3rd Series, XXV, Sec. IV, pp. 85–99. 1931.

[5] Annual Report, Ont. Dept. of Mines, XLII, Part III, pp. 47–78. 1933.



Dominion Observatory, Ottawa W.B.-55

FIG. 11.—Gravity anomaly and thickness of lignite—Onakawana, Ontario.



W.4-34

Fig. 12.—Lines of equal magnetic anomaly from magnetometric survey at Grand Rapids, Mattagami river, Ontario.

7. SIDERITE DEPOSITS AT GRAND RAPIDS OF MATTAGAMI RIVER, MOOSE RIVER BASIN, ONTARIO

Structure.—These deposits have been described by Cross and Dyer.[6] As indicated (Fig. 12), they outcrop in the river bed (at low water) and along the banks. Back of the river banks, siderite and rock formations are buried beneath 50 to 100 feet or more of glacial drift. The iron occurs in large irregular masses in the limestone which for some distance forms the bed of the river and outcrops along the banks. The finding of fossil cores in the iron ore with the corals themselves replaced by iron is noted by Dyer as proof that the siderite deposits were formed by replacement of the limestone. He attributes the origin of the iron to shales which are thought to have overlain the limestone before removal by erosion.

According to Cross,

> "The ore is essentially siderite, although limonite is occasionally present. The limonite is found in vuggy and nodular masses in the siderite, and also forms a thin casing around the margin of the larger siderite bodies. On the whole the limonite forms only a very small percentage of the ore".

Magnetic susceptibilities and densities of numerous rock samples were measured in 1933 (Tables 1 and 2). The most magnetic were diabases taken from the dyke (suspected) not far dowmstream from Pike creek (Fig. 12). Next in order of magnetic susceptibility were specimens of the iron. The best grade of siderite which would be classed as ore appears to be only slightly magnetic. Certain samples of the iron taken from the outcrops were, however, found to be strongly magnetic. It is presumed from their appearance that they were limonite. Densities of the iron ranged from 2·5 to 3·8 (the best grade being heavier) and averaged 3·1. The density of the limestone, which is non-magnetic, ranged from 2·4 to 2·6 and averaged 2·5. That of the rocks from the

TABLE 1—MAGNETIC SUSCEPTIBILITY OF ROCK SPECIMENS FROM GRAND RAPIDS, MATTAGAMI RIVER, ONTARIO

Rock specimen	Number of samples tested	Approximate magnetic susceptibility in units of 10^{-6} c.g.s.	
		Range	Average
Siderite from all outcrops and pits	97	23—6960	958
Siderite from pits 1 to 9	36	23—418	188
Ferruginous sands	2	12—12	12
Greenish sands	1	....	12
Weathered igneous rock	3	70—81	77
Granite	4	12—23	18
Limestone	6	....	0
Lamprophyre from exposure in bed of river, north side	6	46—116	77
Diabase from exposure in bed of river, north side	3	1392—1624	1540
Diabase from exposure in bed of river, south side	3	1160—5800	4250
Greenish rock from exposure in bed of river, south side	13	0—232	90
Conglomerate from exposure in bed of river, north side	2	116—534	325

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[6] Annual Report, Ont. Dept. of Mines, XXXVII, Part VI, 1928, pp. 68-69.

TABLE 2—DENSITY OF ROCK SPECIMENS FROM GRAND RAPIDS, MATTAGAMI RIVER, ONTARIO

Rock specimen	Number of samples tested	Range	Mean density
Siderite	10	2·5—3·8	3·1
Limestone	5	2·4—2·6	2·5
Igneous rock from exposures in bed of river	9	1·9—3·0	2·6
Marine clay			1·9*
Boulder clay			2·3*
Cretaceous clay			2·0*
Muskeg	20	0·1—0·9	0·7

* Determined by Hawkins at Onakawana.

dyke (suspected) ranged from 1·9 to 3·0 and averaged 2·6. Affecting the results possibly, are also rocks of unknown density and susceptibility within the Precambrian, which is thought to lie in the form of a low arch at a depth of a few hundred feet beneath the river bed.

Object of investigation.—At the request of the Acting Deputy Minister of Mines of the Province of Ontario, a preliminary survey was made in 1931 to find out whether it was practicable to outline the possible extension of the siderite in the drift covered area back of the river bank. The survey was resumed in 1933 at the request of the Director of the Ontario Research Foundation.

Topography.—Except quite close to the river, the surface is very flat.

Instruments.—Vertical, and horizontal magnetometers; and two torsion balances.

Date and extent of survey.—In the preliminary survey of 1931, measurements were taken with both vertical and horizontal magnetometers at 90 stations established along traverses, totalling 5 miles, in the vicinity of the ore deposit. Most of this mileage was accounted for by a 3-mile traverse of 20 stations extending southwards from the outcrops at the river bank.

On the journey, by canoe (1931), from Grand rapids to camp at Blacksmith rapids, 35 observations were taken along the Mattagami and Moose rivers to Ship Sands island below Moose Factory and along the Abitibi from its mouth to Blacksmith rapids. These traverses covered a distance of 103 miles and gave some idea of the variation in magnetic intensity throughout the Moose river basin. The traverse up the Abitibi was subsequently continued to Williams island at the foot of Long rapids where a prominent anticlinal fold occurs. At Grand rapids which is 11 miles west of Williams island the folding is flatter and broader but the effect at both places is to bring the Precambrian within about the same proximity to the surface.

In 1933 a grid 1½ miles by ⅔ mile was laid out on the south side of the river so as to include the iron outcrops. Six hundred observations with a vertical magnetometer were taken at intervals of 50 to 100 metres within this and also along three separate traverses. Two of these, each 2¾ miles in length, were along the banks near the water's

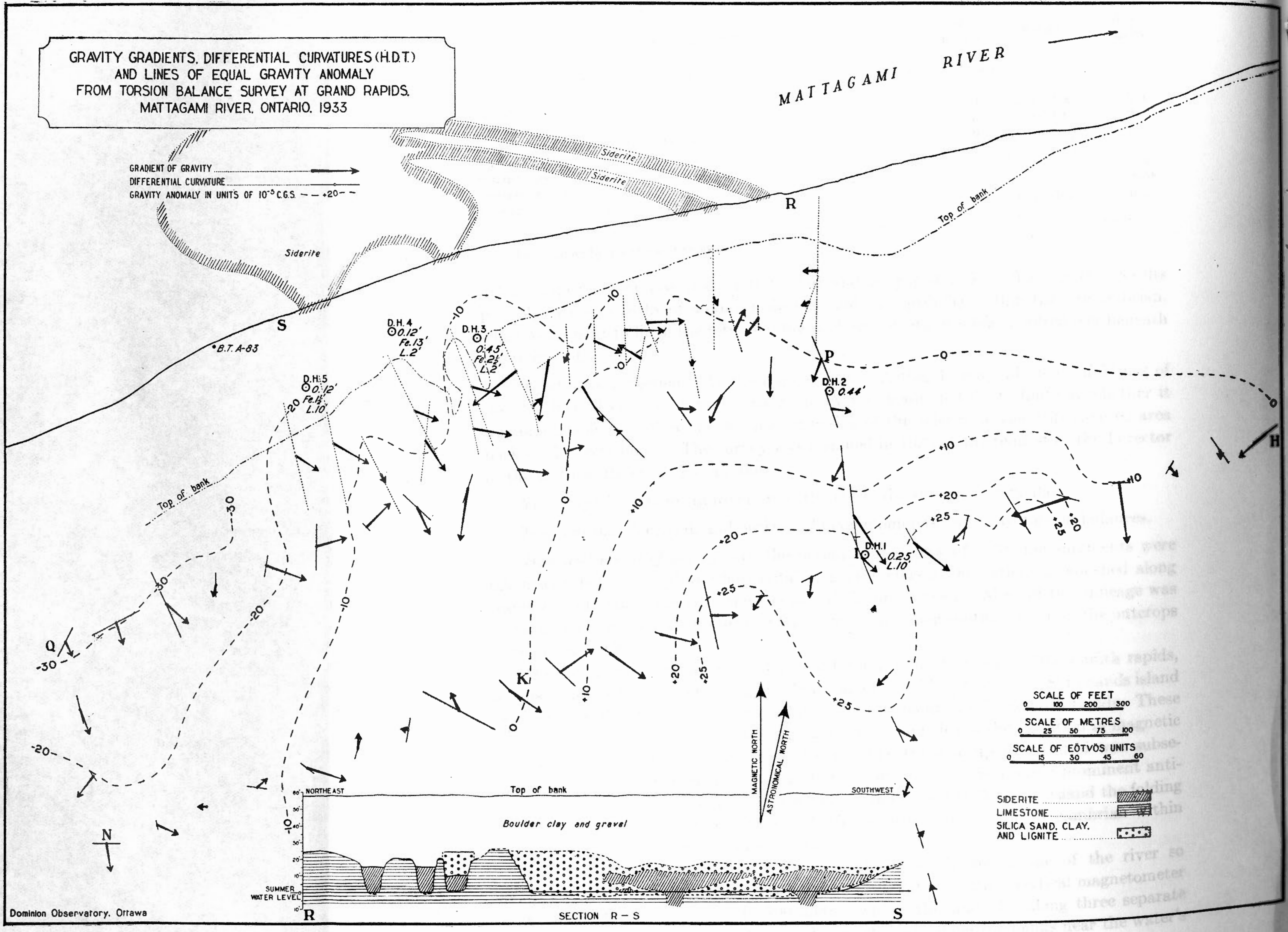

Fig. 13.—Gradients, curvatures, and isogams from torsion balance survey at Grand Rapids, Mattagami river, Ontario.

edge and the third which was $1\frac{1}{2}$ miles long and parallel to the other two was at a distance of $1\frac{1}{3}$ miles from the south bank of the river.

Seventy-three stations were established in 1933 with the torsion balances. For the most part the work with them consisted of a traverse along the line NIH (Fig. 13) and a parallel but somewhat shorter traverse not far from the river bank.

Results.—Magnetometer, and torsion balance: It was concluded from the 1931 results that the magnetic effect of the iron was small and for the most part masked by a larger and more regional effect. By comparison with a similar anomaly observed at Williams island on the Abitibi where the geology is similar except that iron does not occur it seemed likely that the regional effect at Grand rapids was due to the underlying Precambrian. This conslusion was supported by the results of vector intersections of the resultant magnetic anomalies at the two places. Although the main features of the magnetic field were indicated from the 1931 survey, the work of 1933 made it possible to trace accurately the trend and boundaries of the vertical intensity anomalies over a specified area. The new traverse on the north side of the river permitted extension of the contours across the river bed. Other valuable information obtained in 1933 was : (1) tests of the magnetic susceptibility of 100 hand specimens of the iron (Table 1) showed a considerable proportion strongly magnetic and therefore capable of producing an appreciable anomaly; (2) discovery by the geologist (A. R. Crozier) in the river bed at a short distance below Pike creek of weathered exposures of igneous rock apparently of residual origin, and strongly suggesting the presence of a dyke. Diabases taken from it were found to be the most magnetic of any rock samples tested.

Disregarding the negative anomalies to the east (Fig. 12), it is seen that the magnetic field consists of two fairly broad strips of positive anomaly, separated by an intervening negative strip, all trending in an approximately north-south direction. The western strip might be caused by a dyke composed of rock of moderate magnetic susceptibility. The other strip of positive anomaly, extending north and south of the base, includes a considerable proportion of the main iron outcrop and also an outcrop on the north bank. There is also a fairly large outcrop along the eastern border of this anomaly, a few hundred feet off shore to the north of the base. This was not plotted owing to lack of accurate data regarding its position. The geology of a considerable part of the river bed is unknown.

Intersections of resultant anomaly vectors were obtained in the 1931 survey along two north and south traverses. One of the intersections was at a point about 200 feet south of the bank and the main ore body, at a depth of 200 feet or more below the surface, possibly located in iron. The other, a rather indefinite one, was obtained along a traverse from the river bank to a point about one-half mile south of the point I[7] (Fig. 12). This intersection was in the vicinity of I and at a depth of about 800 feet, and thus possibly in the Precambrian. The significance of these intersections would appear to be doubtful, especially as the trend of the anomalies is approximately in the meridian.

Fig. 14 shows the gravity and magnetic (vertical) anomalies along the line NIH (Fig. 12 and 13). The close similarity in the form of the two curves suggests a common origin which would necessarily be a heavy magnetic body, pointing of course to iron.

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[7] Can. J. Res. 10: 473-4. 1934.

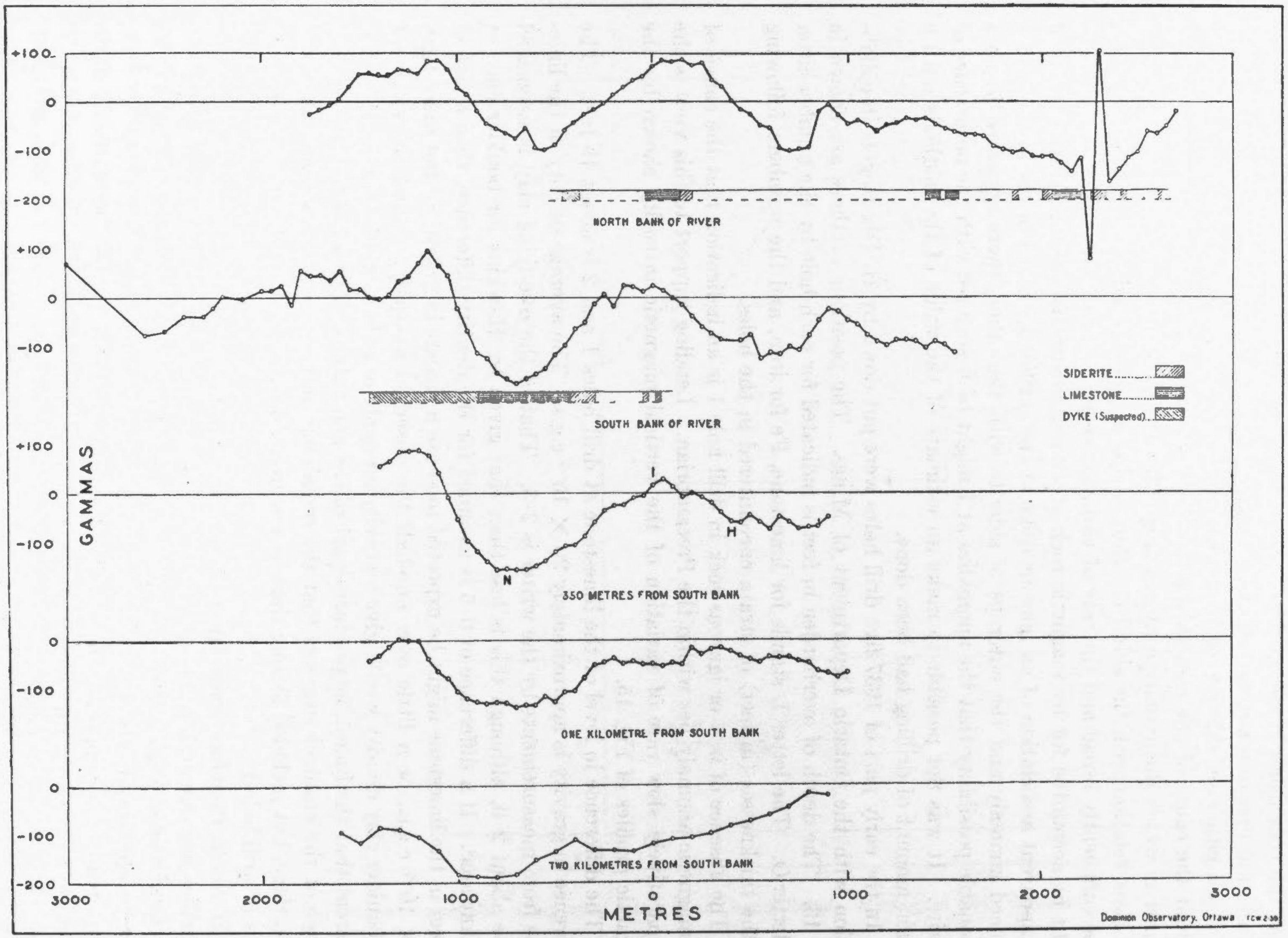

FIG. 15.—Profiles of vertical magnetic intensity along Mattagami river at Grand Rapids, Ontario, and along three approximately parallel traverses south of the right bank. The chainage of the profiles is to the left and right of a line passing through the point I on an astronomical bearing of N 24°17′ W. This line passes about 20 metres west of the base (Fig. 12).

FIG. 15A.—Magnetometers employed at Grand Rapids, Mattagami River, Ontario.

8. BURIED "GRANITE" RIDGE NEAR MONCTON, NEW BRUNSWICK

Structure.—Geology and structural relations are described by G. W. H. Norman in Appendix II.

Tests of some fifty specimens showed that the magnetic rocks were confined to the pre-Carboniferous and consisted of diorite and granite high in biotite and hornblende. Their magnetic susceptibilities ranged from 3,000 to $4{,}000 \times 10^{-6}$ c.g.s. Low susceptibility was indicated by all sedimentary rocks (20 to 40×10^{-6} c.g.s.) and, among the pre-Carboniferous, by altered volcanics, by granite, sheared granite, sheared diorite, and schists.

From the results of several density measurements by the writer and over 200 supplied by Dr. J. A. L. Henderson, it would appear that the average density of the sedimentary formations is not far from 2·5 and that that of the pre-Carboniferous is about 2·7. Not so many measurements were made of the latter, but the result seems reasonable as the average for the pre-Carboniferous is probably not very different from that generally taken for the mean crustal density, namely 2·67. There is of course considerable range in density in the rocks which separately go to make up the two distinctive groups.

Object of investigation.—Definite information regarding the Moncton ridge (it has the grand proportions of a mountain) is confined almost entirely to the section (Fig. 29) immediately to the west of the Petitcodiac river south of Moncton. This has been supplied by the two wells, Nos. 92 and 52, north of Stony creek. It is assumed that the ridge continues to the east and joins the outcrop at Calhoun (Fig. 27). Except from the geophysical results, positive information is lacking regarding the extension of the ridge to the west of the Petitcodiac section.

Was it possible to outline by geophysical methods the boundaries of the buried Moncton ridge? It was to answer this question that the surveys were undertaken.

Topography.—North of Calhoun and of Stony creek the topography is fairly even except for Lutz mountain which has an elevation of 650 feet. North of Meadowbrook on the Calhoun traverse the terrain is for the most part nearly level. Fairly steep slopes occur along the bank of the Petitcodiac for about 2 miles north and south of Stony creek. Apart from this, no great difficulty was encountered in selecting suitable sites for torsion-balance stations. Stony creek cuts out a quite steep valley and the topography to the south and southwest is fairly rough. Caledonia mountain has an elevation of 1,250 feet.

Instruments.—Askania vertical, and horizontal magnetometers, Hotchkiss superdip, and Askania Z type torsion balance.

Date and extent of survey.—Five magnetometric traverses were made in 1932 (Fig. 27) covering altogether about 50 miles. Observations with both the Askania magnetometers and Hotchkiss superdip were made along the Calhoun and main (Petitcodiac) traverses. The Pine Glen traverse was made with the Askania magnetometers. Except for about 2½ miles along Turtle creek, observations on that traverse and across Caledonia mountain were confined to the superdip. Two hundred stations were established (by Norman) with the superdip and about 150 (by the writer) with the vertical, and horizontal magnetometers. In 1935, three traverses were made with the torsion balance covering more or less the same ground as the Calhoun, main, and Pine Glen traverses of

1932 (Fig. 35). One hundred and thirty-one stations were established with the torsion balance, and at each of these stations observations were also made with a vertical magnetometer.

Results.—(a) Magnetometer: Fig. 28 and 29 (Calhoun, and main traverses) show that in certain cases the boundaries of the ridge can be located with precision by the magnetometer. On these two traverses the southern boundary of the ridge corresponds to the maximum horizontal intensity. It is perhaps safe to assume that the same criterion serves to locate the southern boundary along Pine Glen traverse (Fig. 33), and possibly also along Turtle Creek traverse (Fig. 34). The anomalies along this latter traverse although smaller are quite definite, and, when allowance is made for the limited number of observations along Turtle creek, they appear to be similar to those observed along Pine glen and the other traverses. Judging from the form of the curves, the cause of the Turtle creek anomaly lies at greater depth.*

The abrupt termination of the ridge on the south (Fig. 28 and 29) and the associated occurrence of fairly magnetic rock are, of course, favourable to precise determination of this boundary by the anomalies. The manner in which the anomalies appear to peter out at the north end of Calhoun traverse (Fig. 28) is characteristic of a gently dipping magnetized plate, in agreement with the geology. Marked magnetic effects are not observed north of Meadowbrook. On the north of the main traverse (Fig. 29), pronounced magnetic anomalies come to a very abrupt termination just south of the Petitcodiac river at Moncton. This may correspond to a steep boundary in the actual ridge. The anomalies along the main traverse, north of Petitcodiac river, are of a more regional nature and are plainly due to much more deep-seated causes. Observations are comparatively incomplete at the north ends of Pine Glen and Turtle Creek traverses. However, as far as these traverses extend, they indicate again that the area of marked anomaly lies to the south of the Petitcodiac.

Assuming that interpolation may be made between traverses (especially over the long gap between the Calhoun traverse and the main traverse), it is apparent that the magnetic part of the Moncton ridge has been traced for a distance of 10 miles, from the Calhoun traverse to Pine glen. In this area it has a width of 3 to 4 miles, and it occurs along the traverses at an indicated depth of not more than 500 feet. The observations along Turtle creek suggest that west of Pine glen the ridge pitches westwards occurring at an indicated depth of 1,000 to 1,500 feet at Turtle creek.† Owing to the fact that some of the pre-Carboniferous formations are only slightly magnetic, as indicated by the Caledonia Mountain traverse (Fig. 32) and by tests of rock samples, it is possible that the magnetic ridge forms only a part of the actual ridge, although it may constitute a

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* The form of the curves along the Calhoun traverse (where the pre-Carboniferous is exposed) indicate, for the two main disturbances, magnetic poles at depths of 500 to 600 feet. Rather poorly defined vector intersections occur at about 1,000 feet. Along the main traverse, where the depth to the pre-Carboniferous is about 500 feet, the curves indicate a depth of 1,500 to 2,000 feet, and the vectors about 2,000 feet. On Pine glen the curves indicate again a depth to magnetic pole of 1,500 to 2,000 feet, and the vectors 1,500 feet. The Turtle creek curves (Fig. 34) indicate a depth of 3,000 feet. It is therefore likely that the depth to the pre-Carboniferous is about 500 feet along Pine glen, and probably from 1,000 to 1,500 feet along Turtle creek. The diminution in anomaly can be accounted for by such an increase in depth.

† Turtle creek is six miles west of Pine glen.

very considerable proportion. Depth[9] determinations which are confined to the magnetic part of the ridge are only very approximate. It is apparent that the ridge can be detected by its magnetic influence to a depth of 1,000 to 1,500 feet.

Where the Moncton ridge approaches the surface, the oil and gas bearing Albert shales are absent. Location of the ridge thus means that in the search for these minerals unfavourable or barren areas can be excluded from expensive drilling operations. A considerable part, apparently about 50 square miles* of this ridge, has been outlined by the surveys illustrated in this report. Further observations would probably serve to fix some of the boundaries more accurately.

Very little can be concluded from the geophysical results regarding depth to the pre-Carboniferous in the area outside the magnetic part of the ridge. The gravity anomaly along the main traverse (Fig. 36), interpreted in terms of the average in density between the sedimentary and pre-Carboniferous formations, indicates a thickness of about 7,500 feet for the sedimentary (at Weldon), and this agrees well with the depth 10,000 deduced from the geology. On this basis the thickness of the sedimentary formations, where the main traverse crosses the Petitcodiac river at Moncton, would be about 5,000 feet. However, this may not be the correct interpretation. The gravity anomaly along the Calhoun traverse is incapable of any such interpretation.

(b) Torsion balance: Except for the above mentioned apparent relation along the main traverse between the gravity anomaly and depth to the pre-Carboniferous, the torsion balance results appear to be of little value in so far as the main object of the investigation is concerned.

Along the north half of the Calhoun traverse, there is a uniformity in the results which enables interpretation of the underlying structures to be made. If it were certain that these were pre-Carboniferous, then the results could be used to estimate depths to that formation. For example, near the north end of the traverse at Scadouc station an anticlinal structure (or ridge) is definitely indicated by the gradients and curvatures. It is apparent that they could be accounted for by such a structure at a depth of about 200 metres. At this same point, a small but definite anomaly occurs in the magnetic intensity. A similar structure with similar relations between the gravity and magnetic results is indicated about 3 miles to the south. About one mile still further, another rise is indicated with no corresponding magnetic effect. With sufficient analysis and patience, there could be deduced the form of a subterranean surface which would produce the observed gravitational effects. The gravity anomaly over the whole of the Calhoun traverse would indicate that this surface could hardly represent the pre-Carboniferous, unless the density of this formation increases progressively to the north. Similar interpretation along the northern part of the main traverse might also be possible with the establishment of a closer series of stations.

The main gravity anomalies are large enough to be measured with a gravimeter or a pendulum apparatus.

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[9] For a summary of "Depth Rules" for use with magnetic anomalies see A.I.M.E., Geophysical Prospecting, 1932, p. 213, and Tech. Pub. No. 830.

* Making allowance for the reservations stipulated at the beginning of the preceding paragraph.

9. Malagash Salt Deposit

Structure.—Geology[10] and structural relations have been described by G. W. H. Norman as follows:—

> "The consolidated rocks at Malagash are a part of the Cumberland basin of folded Carboniferous strata. This basin is geosynclinal in structure, and extends eastward from Chignecto bay across the northern part of Nova Scotia. The Carboniferous strata of the basin consist of a lower group, Mississippian in age, of soft, prevailingly red shales and some sandstone with intercalated beds of gypsum, anhydrite, salt, and fossiliferous marine limestone, and an upper group, Pennsylvanian in age, of sandstone, conglomerate, and shale, in places containing coal seams. The Mississippian strata are brought to the surface only along anticlinal folds, and are poorly exposed on account of their chemical and physical character. The anticlinal structure that brings the Mississippian rocks to the surface at Malagash extends southwestward from Malagash for about 40 miles. The south limb of this anticline dips steeply south at 45 to 75 degrees. The north limb is overturned in many places, and apparently is broken by thrust faults. The Mississippian rocks occur at the surface along this anticline as alternating broad and narrow masses, and are complexly contorted in contrast with the more uniform structure of the Pennsylvanian rocks on either limb.
>
> The succession and character of the strata present at Malagash are as follows:—
>
> | | | |
> |---|---|---|
> | Pennsylvanian | Pictou series | Red shale, sandstone, and conglomerate |
> | | Unconformity | |
> | | Boss Point formation | Massive red, gray, to buff sandstone, with interbedded red and some gray shale |
> | Mississippian | Windsor series | Red shale, sandstone, soft gray shale, interbeds of gypsum and limestone |
> | | Windsor series (?) | Salt and interbedded gray and red shale |
>
> These formations are concealed beneath about 25 feet of boulder clay, except along the shore at low tide, as indicated by Fig. 16, which shows the relative position of outcrops to the salt of the mine workings. The levels in this figure serve as structure contours of the Lucas salt seam, which is one of the purer beds of salt in the upper part of the salt strata.
>
> The salt strata, explored by the mine workings and by drill holes, have a thickness of about 300 feet and consist of pure salt interstratified with impure salt, and red and gray shale impregnated with salt. Salt, making allowances for clay in the impure beds, amounts to about 65 per cent or so of the total thickness. The character of about 1,000 feet of strata that lie on either side of the salt is known only very imperfectly, from a few shallow drill holes along and near the salt. The holes indicate that the unexposed strata on either side of the salt include red shale and sandstone, gypsum and gypsiferous clays. It is possible that they are a part of the Windsor series that is poorly exposed on the shore, a third of a mile north of the shaft. The Boss Point formation outcrops only along the shore and is overturned toward the north. The Boss Point strata rest with little if any discordance on the Windsor strata in the Cumberland basin, and at Malagash their contact is possibly along a fault. The Pictou strata have gentle north dips on the shore north of the mine and rest unconformably on the upturned edges of the Boss Point formation. Although the Pictou strata are not exposed immediately south of the mine, except for one doubtful outcrop, they are inferred to underlie a prominent ridge that lies about 1,200 feet south of the shaft, and they outcrop with steep south dips in a westward extension of this ridge.
>
> The salt strata at Malagash probably form part of a domelike structure on a faulted anticline that strikes east. That possibly all or at least the more southerly and uppermost salt beds in the mine are a part of the south limb of the structure is suggested by the consecutive order from north to south of anhydrite, salt, and potash-bearing salt that occurs in a small thickness of the uppermost beds. The north limb of the structure, which is partly exposed on the shore (Fig. 16) beneath the gently dipping Pictou strata, is overturned and is probably broken by thrust faults, as the distance from the base of the Boss Point formation to the salt is insufficient to include the thickness of strata that occurs in this interval in other parts of the Cumberland basin. The salt strata are contorted into steeply plunging folds whose axial planes strike across the anticline, parallel to a series of north-northwest faults in

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[10] The following references furnish further information regarding the geology:—

H. Fletcher. Malagash Sheet No. 60; Geol. Surv. Can.

A. O. Hayes. The Malagash Salt Deposit, Cumberland County, N.S., Geol. Surv. Can., Memoir 121. 1920.

W. A. Bell. Carboniferous Formations of Northumberland Strait, Nova Scotia. Geol. Surv. Can. Summ. Rept. (1924), Part C, 142–180.

G. W. H. Norman. Salt Deposits of Nova Scotia and New Brunswick. Geol. Surv. Can. Summ. Rept. (1931), Part D, 28–35.

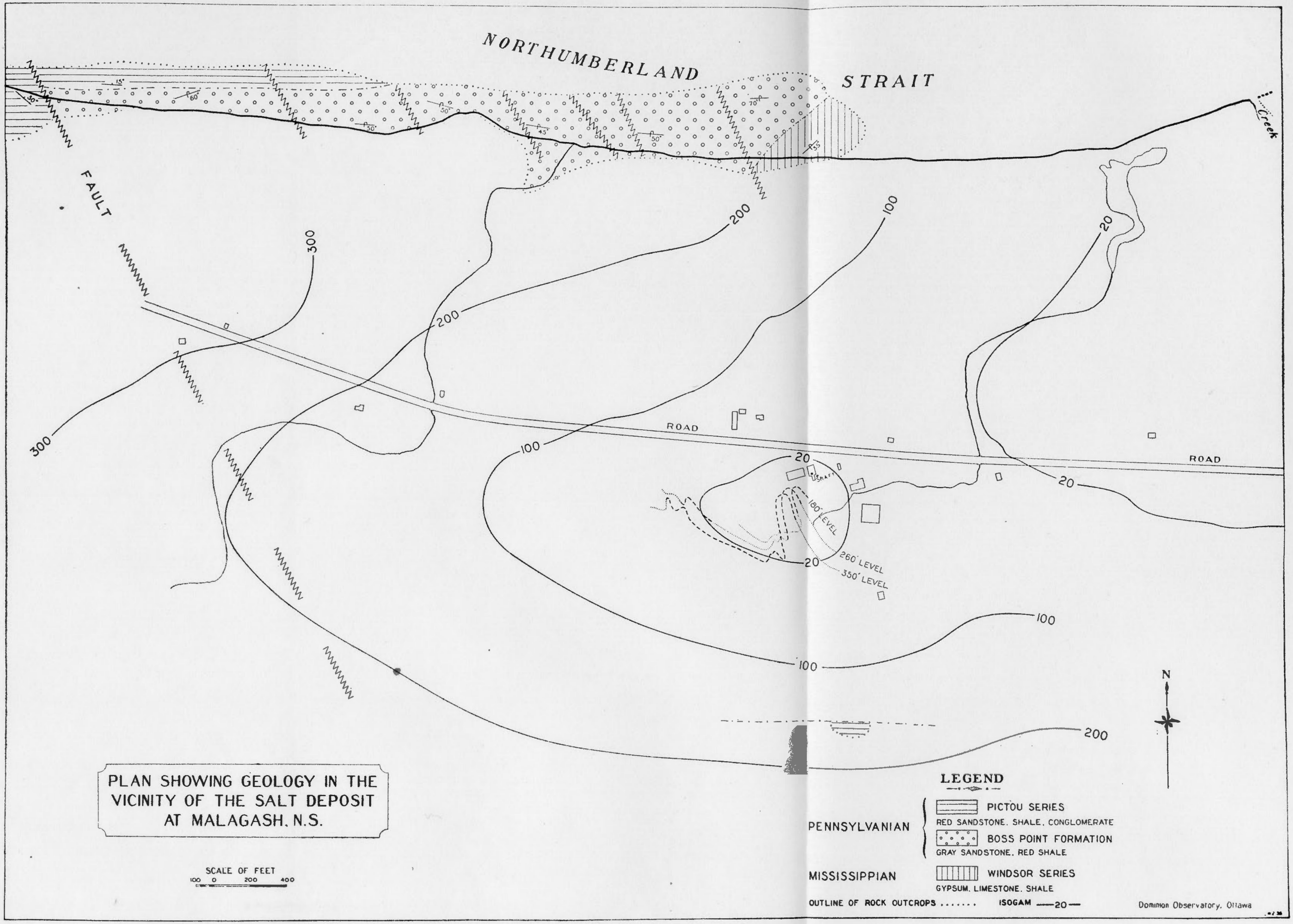

FIG. 16.—Geology in vicinity of salt deposit at Malagash, Nova Scotia.

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s have been described by G. W. H.

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Northumberland Strait across the northern part of Nova
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Geol. Surv. Can., Memoir 121

near Nova Scotia. Geol. Surv. Can. Summ.

Geol. Surv. Can. Summ. Rept.

the more competent strata on the shore. The majority of these transverse faults on the shore are small, but one that lies about 3,200 feet west of the shaft has a downthrow of 500 feet or more on its west side. The most easterly of the cross faults on the shore should pass a short distance east of the shaft, if it parallels the other faults. But as the outcrops along this part of the shore end about 400 feet east of this fault, its magnitude and the probable location of salt east of it are unknown."

Before the survey was undertaken twenty-seven samples of rocks including salt were collected at Malagash for density tests, the results of which were as follows:—

Formation	Rock	Number tested	Range in density	Mean
Windsor	Salt	5	2·14—2·24	2·16
Windsor	Impure salt	3	2·16—2·21	2·18
Windsor	Gray clay	1		2·15
Windsor	Yellow shale	2	2·17—2·30	2·23
Windsor	Red shale	1		2·50
Windsor	Sandstone	2	2·32—2·61	2·48
Windsor	Gypsum			2·30*
Boss Point	Red shale	1		2·56
Boss Point	Sandstone	5	2·25—2·45	2·33
Pictou	Sandstone	5	2·32—2·67	2·45
Pictou	Conglomerate	2	2·35—2·38	2·36

* This value was taken from the Smithsonian Physical Tables.

The measurements indicated that the density of the rocks is rather low but that on the average it exceeds that of salt by 0·2. Some of the rock samples have very nearly the same density as the salt but these, with the exception of Windsor gray clay from the shore a third of a mile north of the shaft, were taken from the salt-bearing shales that are interstratified with the salt in the mine.

Object of investigation.—This deposit lies on the north shore of Nova Scotia about 40 miles east of the New Brunswick boundary, and forms a part of faulted and folded Carboniferous strata. The salt beds are exposed only in the mine workings, which are about 1,000 feet deep and at one place extend for 1,000 feet along the strike. Lack of rock exposures, complicated folds, and faults make it impossible to predict the location of the salt away from the mine. A survey of an area in the vicinity of the mine was therefore undertaken to find out whether the salt could be located by the torsion balance and whether its extension from the mine workings could be traced. As the gravitational effects at Malagash may be fairly typical of those at other concealed salt deposits in the Carboniferous rocks of the Maritime Provinces, the survey has a direct bearing on prospecting for other deposits.

Topography.—This ranged from flat to gently undulating. The difference in elevation between the highest and lowest torsion balance station was about 100 feet.

Instruments.—Two torsion balances, one photograpically recording, the other visual.

Date and extent of survey.—The survey was made in 1934. An area of about three-quarters of a square mile was covered with 233 stations. Thirty-six of these were observed with the visual instrument.

Results.—The results of the survey are illustrated in Fig. 17, which shows the gradients, curvatures, and isogams or lines of equal gravity. The total anomaly measured is about 300×10^{-5} c.g.s., or 0·003 c.g.s.

The isogam contour 20, which is drawn about the shaft, outlines an area of low density under which salt is known to exist. It is most likely, as indicated by computation also, that the gravitational anomalies in the immediate vicinity of the mine are mainly due to the occurrence of salt. The gradients over the known deposit are directed away from the salt, and the curvature is large over it and at right angles to the general strike of the salt beds. The location of the westward extension of the salt from the mine is probably fairly well indicated by the line of maximum curvatures and minimum gradients that extends west from the centre of the area of low gravity at the shaft. The results show that an area of low gravity comparable to that over the known deposit occurs east of the shaft. There is only a small rise in gravity over the ground separating the two areas of low gravity. The results over this second area are obviously an indication of salt or other rock of low density. Towards the completion of the survey a shallow drill hole was put down about 100 feet west of station 215 in the southwestern part of this area and vertical strata of light reddish shale were encountered. The densities of three samples from the drill core were found to be almost precisely the same as that of salt. This does not, however, necessarily preclude the existence of salt in other parts of this area. Whether this area contains a deposit of salt of commercial importance cannot be settled until the area is adequately explored. If salt is present, it probably occurs at about the same depth as at the mine.

An attempt has not been made to compute a hypothetical structure that would fit the observed results. It is felt that, even if such a solution were made, little could be definitely asserted from the results regarding the minor folds in which the salt lies. The pattern of isogams and gradients over the western three-quarters of Fig. 17 is suggestive of a dome plunging uniformly westwards and broken eastwards. However, a lens-shaped mass of rocks of low density, dipping vertically or nearly so and thinning westwards either horizontally or vertically or in both these directions, might produce a similar pattern. Whether the salt is merely folded into its present position, or has been forced upwards through younger strata as an intrusive mass, cannot, of course, be determined from the results.

Combined with the more apparent causes of disturbance in the gravitational field, there are no doubt other causes that contribute to the general result. Some of these are quite possibly due to subterranean conditions which may differ from those existing near the surface. It seems probable also that the Mississippian rocks taken as a group are of lower density than the Pennsylvanian strata. This is indicated by density measurements and is also suggested by the large gradients and distinct change in direction of curvature that apparently mark the concealed contact of the Windsor and Boss Point formations between the shore north of the mine and the main cross fault to the west of the mine. There are no very apparent gravitational effects associated with any of the cross faults, not even with the largest. The displacements along these faults would seem, therefore, to involve only minor disturbances of density.

Neither the gradients nor isogams shown in Fig. 17 have been corrected for the salt that has been taken out of the mine. There is doubtless an appreciable effect due to

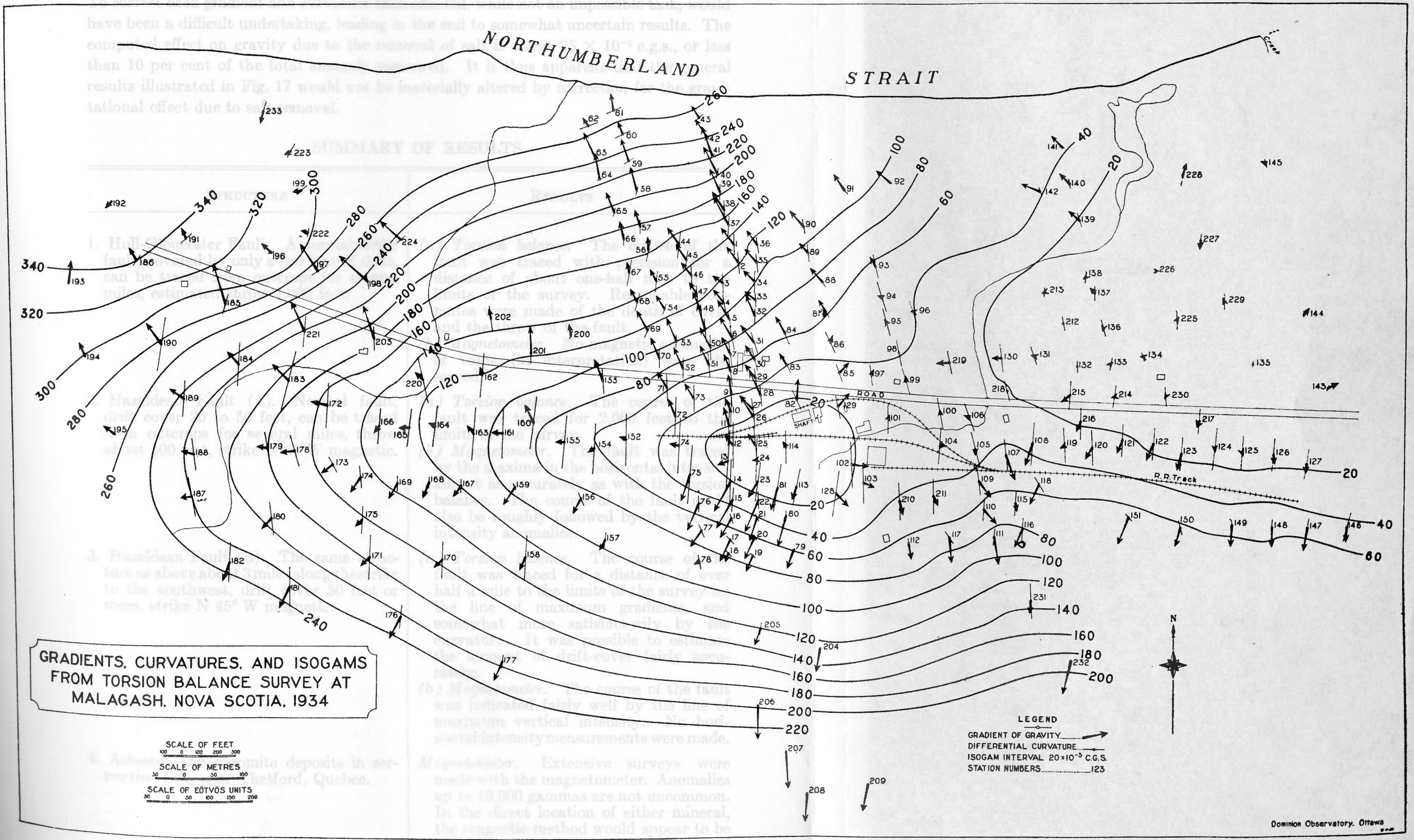

FIG. 17.—Gradients, curvatures, and isogams from torsion balance survey at Malagash, Nova Scotia. At stations where gradient arrows are not shown, the gradients are too small to be plotted. Curvature corrections for certain stations near the borders of the figure could not be computed owing to lack of data regarding elevations.

SUMMARY OF RESULTS—*Continued*

STRUCTURE	RESULTS
5. Caldwell Pyrite deposit, Renfrew county, Ontario.	(*a*) *Torsion balance.* The pattern of isogams, deduced from the gradients, outlined the area in which the bulk of the ore is concentrated. From the asymmetry of the gradient profile across the main ore mass, an accurate determination of the dip of the ore body was made. (*b*) *Magnetometer.* Although the magnetic intensity was by no means uniform over the area covered by the magnetometer, it was only in the vicinity of the deposits or outcrops that large anomalies were observed. The trend of the deposits was indicated by the anomalies.
6. Onakawana Lignite deposit.	*Torsion balance.* In a traverse of 4 miles, barren and mineralized regions were indicated by the magnitude of the gravity anomaly. Bore holes in any of the three pronounced gravity lows would strike lignite, and in two out of the three cases at the thickest points of the seams. Fair estimates of the thickness of the seams could be made from the gravity differences.
7. Siderite deposit at the Grand rapids of the Mattagami river, Moose River basin, Ontario.	Surveys with the magnetometer and traverses with the torsion balance, combined with the results of drilling, indicate that the magnetometer is of little or no value in locating these deposits, and that under the probable conditions of occurrence of the iron it is very doubtful if the torsion balance is of any value either.
8. Buried "Granite" ridge near Moncton, New Brunswick.	Natural gas and oil are mined in the Stony Creek field to the south of Moncton. The boundaries of the Moncton ridge outline an area in which these minerals are unlikely to occur. Location of the ridge thus makes it possible to exclude unfavourable or barren areas from expensive drilling operations. About 50 square miles representing the magnetic part of the ridge were outlined with the magnetometer. This probably forms a considerable part of the actual ridge. Along the main traverse, where the anomaly is ·016 c.g.s., there appears to be a close relation between the gravity anomaly, the magnetic anomaly, and the

SUMMARY OF RESULTS—*Concluded*

STRUCTURE	RESULTS
8. Buried "Granite" ridge near Moncton, New Brunswick—*Concluded.*	ridge. However, the results of three torsion balance traverses tend to indicate that the torsion balance would not be of great value in this problem. The gravitational results are certainly of less value than the magnetic.
9. Salt deposit at Malagash, Nova Scotia.	This deposit was accurately located by the torsion balance, and there is reason to believe that the instrument would be of value in the location of similar deposits.

CONCLUSION

The three preliminary investigations show that the torsion balance is useful in tracing faults, and that for this purpose the magnetometer is also of considerable value. The work at Thetford with the magnetometer shows that this instrument is of value in locating drift-covered boundaries of the serpentine belt and dykes, such as the Pennington dyke. In the direct location of either chromite or asbestos, the magnetometer appears to be of no value. The results at Caldwell mine suggest that both the magnetometer and the torsion balance might prove of value in outlining minerals, or in outlining structures associated with minerals in other Precambrian areas. The traverse at Onakawana indicates that areas favourable to the occurrence of lignite could be outlined with the torsion balance. Neither the torsion balance nor the magnetometer appears to be of much use in locating iron deposits under the conditions in which they appear to occur at Grand rapids. The magnetometer is useful in locating buried ridges such as the Moncton ridge, and the torsion balance would probably be useful in outlining deposits similar to the Malagash salt deposit.

In prospecting with either of these instruments, a much more difficult problem is presented than in making tests over known deposits. In addition to familiarity with fundamental principles and with the geology of the problem, there is required skill in interpretation for which not only ability is necessary but evidently, in addition, much experience in the application of the methods.

Geophysical methods have their place in prospecting, because the discovery of valuable minerals is difficult and expensive. Drilling and excavation costs, which are usually very high and may even be prohibitive, can often be very much reduced by making a geophysical survey. Costs of a geophysical survey are, however, by no means inconsiderable. A torsion balance costs about $4,000, and a magnetometer about $600. It has been estimated that the cost per station with the torsion balance[11] is $10 to $15, and with the magnetometer[12] $1 to $1.50. Costs of operation and the nature of the

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[11] Directions for the Use of the Askania Torsion Balance, 1933.—C. A. Heiland.

[12] Manual on Geophysical Prospecting with the Magnetometer.—J. Wallace Joyce.

topography limit the field of application of the torsion balance. Where anomalies exceed 500 gammas, much useful work can be rapidly performed by a competent observer with less expensive types of magnetometer, for example the ordinary dip needle.

Although it was not found possible to carry on the investigations in the systematic manner that was originally intended, there have nevertheless been investigated a number of typical and important geological structures, and several other problems actually or potentially of great practical importance. As might be expected, the apparent value of the methods has varied much from one problem to another. In some problems, the methods appeared to have little or no application, while in other problems they appeared to be very useful.

There remains, however, the fact that, out of the limited number of problems described, there are several cases where these instruments were distinctly applicable. That there are many other similar problems in Canada, where they could be successfully applied, can hardly be doubted, especially when allowance is made for future development of the methods.

APPENDIX I—MAGNETIC FIELD OF PENNINGTON DYKE

By A. H. Miller

ABSTRACT.—As part of a considerable amount of investigation carried on by the Dominion Observatory and the Geological Survey of Canada, during the seasons from 1930 to 1932, on the applicability of magnetic instruments to the problem of locating asbestos and chromite deposits in the Thetford area of Quebec, a number of traverses were made of the Pennington dyke. Twelve of these with a vertical magnetometer, three with a horizontal magnetometer, a dip needle, and a Brunton compass, and one traverse with a Hotchkiss superdip, show that for a considerable part of its length the dyke can be located beneath the existing drift cover by any of these instruments. The results of the measurements are compared graphically in seven profiles.

They indicate that the magnetism of the dyke is induced by the magnetic field of the earth, and that, approximately, the field of the structure can be explained on the assumption that it is uniformly magnetized.

Results obtained with the superdip are dealt with in a separate section of the paper.

INTRODUCTION

The Pennington Dyke[1].—This is the name given locally to the long dyke, or series of dykes, extending in an easterly direction from the Pennington mine in the vicinity of Thetford, Quebec, and traceable by fairly numerous outcrops for a distance of about 7 miles to Rumpleville. From here on, for a distance of 2 or 3 miles, no outcrops occur, but what may be the same dyke appears on the same line of strike and is traceable through the Quebec Asbestos, Fraser, and Boston mines for a further distance of about 3 miles. In regions where the outcrops occur, the dyke is in many intermediate places entirely covered with drift, varying in thickness from a few feet to perhaps as much as fifty feet. Throughout its length, it is composed for the most part of serpentine. In certain places, it has been either partially or entirely altered to soapstone. Frequently, veins of asbestos are to be found in the serpentine, so that the dyke has been mined in several places for asbestos and in at least two for talc, or soapstone. The dyke varies in width from somewhat more than one hundred feet to perhaps seven or eight hundred feet. It strikes in a direction of approximately 70 degrees to the east of magnetic north, and dips on the average from 60 to 70 degrees to the southeast. The dyke itself is an intrusion into sedimentary beds of slates and quartzites. As the bedding of the sedimentary strata largely controls the dip of the dyke, it is to be expected that both extend to great depths. In addition, the slates and quartzites are to be found for some miles on either side of the dyke.

Traverses.—The dyke was traversed in twelve places with an Askania vertical magnetometer, but in only three places with both vertical and horizontal magnetometers. At these three places the serpentine is highly magnetic, and there are asbestos pits within a few hundred feet of the traverses. It is believed that the results for the two traverses, selected for this paper, are fairly illustrative of the magnetic field of the dyke, at places where it is composed of the more magnetic variety of serpentine. From a limited number of observations along the strike, it would appear that the variation of anomaly in that direction is relatively small.

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[1] H. C. Cooke. Thetford Map Area, Quebec. Summ. Rept., Geol. Surv., Part D. 1930.

——— Asbestos Deposits of Thetford, Quebec, Part D. 1931

Magnetic susceptibilities of rock specimens.—Susceptibilities of rock specimens were determined by a method described by Koenigsberger.[2] Slates and quartzites gave values up to 70×10^{-6} c.g.s. That of soapstone was too small to measure. Susceptibility of the serpentine varied over a wide range up to $16{,}000 \times 10^{-6}$ c.g.s. The measurements indicate that as a rule the susceptibility of the serpentine is greater than $1{,}000 \times 10^{-6}$ c.g.s. Where asbestos veining occurs, it is usually much greater, being of the order of $10{,}000 \times 10^{-6}$ c.g.s.

DISCUSSION OF RESULTS

TRAVERSE I

Location.—This traverse was made at the Federal mine about one and one-half miles east of traverse II. Along traverse I the surface of the dyke is entirely exposed, having been laid bare by the removal of about 10 feet of drift. Although the positions of the contact of the dyke with the slates and quartzites on either side are known precisely, the conditions of the traverse were not entirely ideal, because, at a distance of about 50 to 60 feet east of the traverse, the dyke had been excavated to a depth of about 40 feet. At distances of about 50 feet from the contacts, the stations are located on the drift and are therefore somewhat higher than the upper surface of the dyke. At every station the height of the instrument was about four feet above the surface of the ground. The elevations of the stations have been taken account of in computing the theoretical results. The differences due to this cause are comparatively small.

Instruments.—The dyke was traversed with (1) Askania horizontal, and vertical magnetometers to measure the anomalies in the horizontal, and vertical intensities, (2) a five-inch Cooke theodolite to obtain the declination anomalies, and (3) a Gurley dip needle.[3]

Observed anomalies.—The values of ΔT (Fig. 18) were computed from the observed values of ΔZ and ΔH by means of formula (3). The values obtained for traverse II by this formula were compared with those obtained with the exact formula (4), and it was found that, even for anomalies up to 7,000 gammas, the approximate formula was in error by as much as 250 gammas in only one case (chainage 1,750, the station of maximum dip anomaly). Usually the error was less than 100 gammas. The close agreement between the ΔT and ΔZ curves (Fig. 18) brings out very clearly the fact that in these latitudes the greater part of the total intensity anomaly is due to the vertical component and that variometers designed for the measurement of these anomalies are actually measuring more or less the same effect.

The anomalies indicated by the curve ΔH_T are not the anomalies in the plane of the magnetic meridian which varies from station to station, but are the anomalies in the horizontal plane, parallel to the direction of the traverse. They have been computed from formula (5). Both traverses were at right angles to the strike of the dyke.

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[2] J. G. Koenigsberger. Method for Measuring the Susceptibility of Rocks. Terrestrial Magnetism and Atmospheric Electricity, Vol. 34, No. 3, pp. 209–214, September, 1929.

[3] Noel H. Stearn. The Dip Needle as a Geological Instrument. Geophysical Prospecting, pp. 345–363, A.I.M.E., 1929.

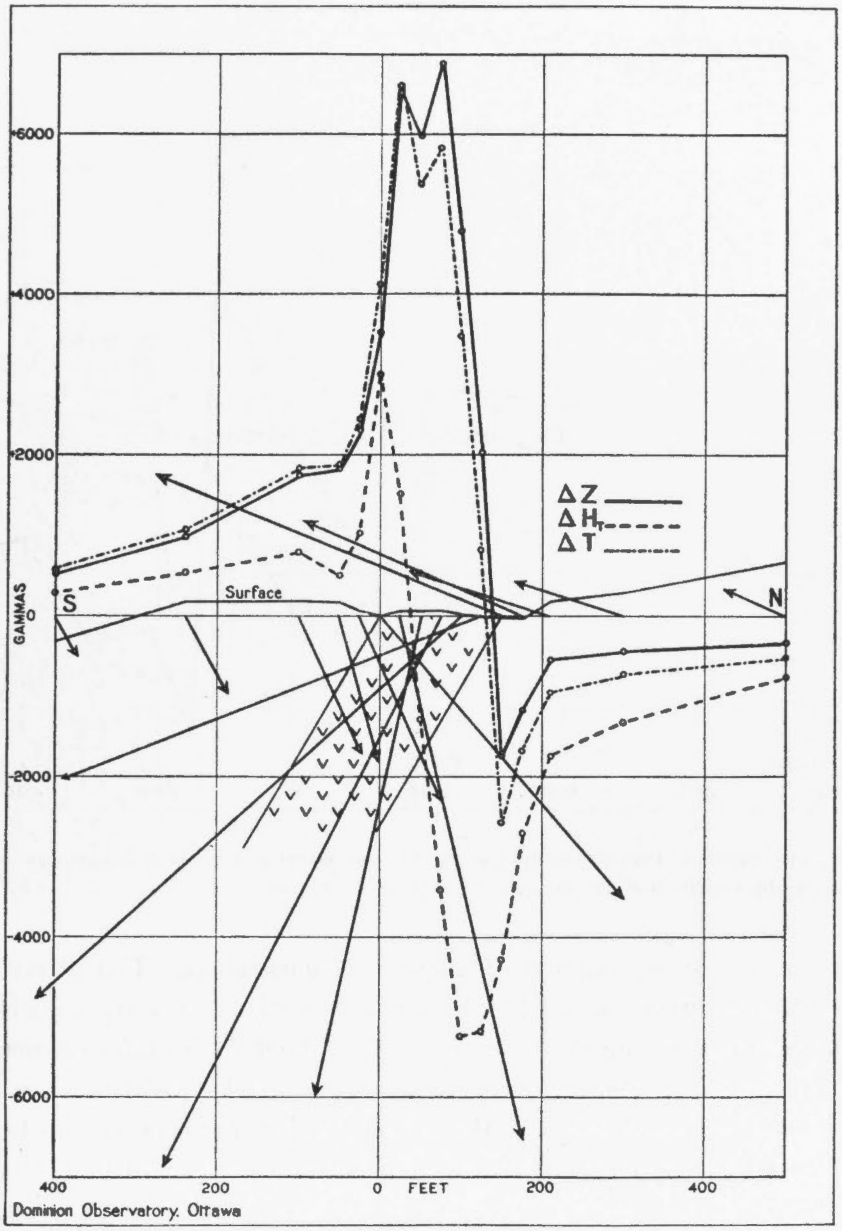

FIG. 18.—Magnetic profile of Pennington dyke at the Federal Asbestos mine, near Robertsonville, Quebec, showing anomalies in the vertical, horizontal, and total intensities, and also the anomaly vectors (traverse I).

The values of ΔI, plotted in Fig. 19, were not observed, but were computed from the Askania results by means of formula (6). This formula gave values agreeing (within a few minutes) with those obtained from the theoretically exact formula (7) and also with the results for traverse II, obtained by actual measurement with the Hotchkiss superdip used as an ordinary terrestrial dipping needle. The anomaly vectors in the various figures were obtained graphically, by vector addition, from the corresponding values of ΔH_T and ΔZ.

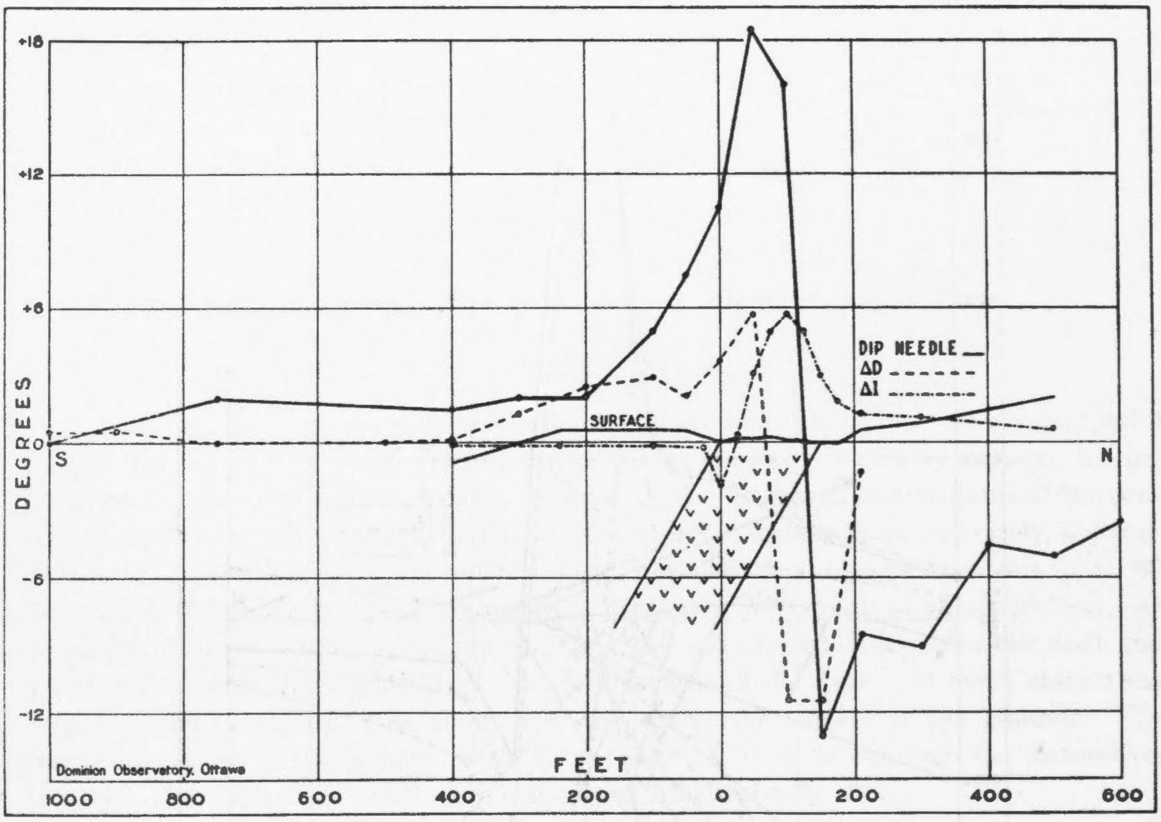

Fig. 19.—Magnetic profile of Pennington dyke at the Federal Asbestos mine, near Robertsonville, Quebec, showing dip needle, declination, and dip anomalies (traverse I).

Theoretical values on assumption of uniform magnetization.—The plotted values in Fig. 20 are neither observed nor deduced from observations, but are theoretical values computed from formulae (8) on the assumption that the dyke is uniformly magnetized by influence of the earth's magnetic field. There is sufficient similarity between Fig. 18 and 20 to show that in a general way the magnetization of the dyke can be accounted for by the assumption that has been made. It seems possible that the results might also be interpreted in terms of a magnet inclined to the north with the upper (south) pole at a depth of about 40 feet, but they would apparently necessitate the other pole lying within the slates and quartzites.

Anomaly vectors.—A point of special interest in connection with Fig. 20 is the intersection of the anomaly vectors at about the same point as that of the observed vectors (Fig. 18). In Fig. 20 the intersection has no physical significance, in the sense of the point being a centre for the accumulation of magnetic charge, because the directions of the vectors are computed on the assumption that the free charge is confined to the surface of the dyke. It is therefore apparent that these intersections may sometimes be due to certain surface distributions of charge, and it is conceivable that in some cases the intersections might occur at points outside the magnetic structures altogether. For

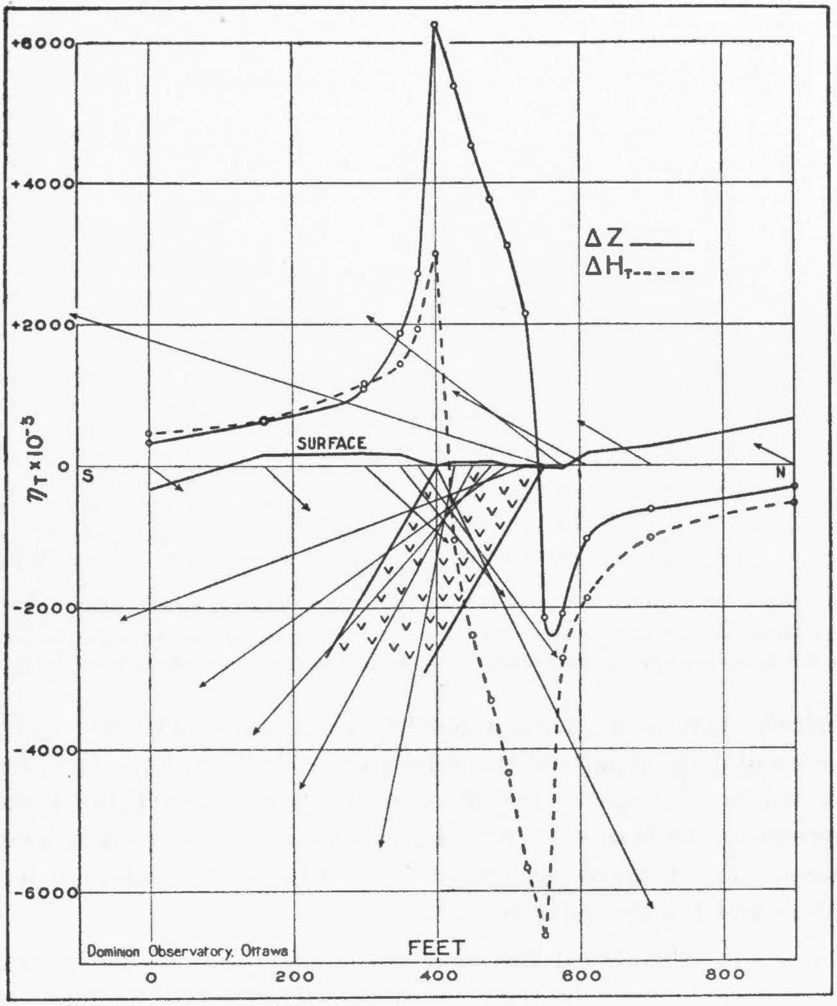

Fig. 20.—Theoretical magnetic profile of Pennington dyke at the Federal Asbestos mine, near Robertsonville, Quebec, showing the computed anomalies in vertical and horizontal intensities, and anomaly vectors (traverse I).

the two traverses, the intersections are within the structures but at depths which differ by amounts which do not likely represent, even within a considerable margin, the difference of drift cover.

Declination and dip anomalies.—In Fig. 19 positive values of the declination anomalies indicate a deflection of the compass needle to the west. The anomalies in both declination and dip agree with those to be expected from the magnetization of the dyke inferred from the anomalies in the other magnetic elements. The marked asymmetry in the dip curve is due to the large negative anomaly in the horizontal intensity coupled with a low value of the vertical intensity on the north side of the dyke. The asymmetry in the declination anomaly curve is of course due to the negative anomaly in the horizontal intensity on the north side being considerably larger, numerically, than the positive anomaly to the south. Comparison of the dip-needle anomalies (in degrees) with ΔT in Fig. 18 shows that one degree of the dip needle corresponds on the average to an anomaly of about 250 gammas.

Positions of maxima and minima.—Other points of importance in connection with the curves of Fig. 18, 19, and 20 are summarized in Tables 3 and 4. In these tables the points at which the various magnetic anomalies are a maximum, zero, and a minimum are given in terms of decimal parts of the dyke width. In Table 3 the observed maximum and minimum values (traverse I) are given in gammas, and in Table 4 the computed values are expressed in units of $\eta_T \times 10^{-3}$, a unit which in this case is not very different from one gamma. The distances are measured from the south contact, 0·0 representing the south contact and 1·0 the north contact.

TABLE 3—LOCATION OF MAXIMUM AND MINIMUM MAGNETIC EFFECTS OBSERVED IN TRAVERSE I OF PENNINGTON DYKE.

Anomaly	Maximum		Zero	Minimum	
	Position	Value	Position	Position	Value
ΔZ	0·5	6878γ	0·9	1·0	-1748γ
ΔH_T	0·0	3000γ	0·2	0·8	-5247γ
ΔT	0·2	6617γ	0·9	1·0	-2575γ
Dip Needle	0·3	18°5	0·9	1·0	−13°
Dip	0·7	+5°7	0·1	0·0	− 1°9
Declination	0·3*	5°7	0·4	0·8	−11°4

* At two other traverses the maximum westerly declination occurred a few feet to the south of the south contact.

TABLE 4—THEORETICAL POSITIONS OF MAXIMUM AND MINIMUM MAGNETIC INTENSITIES FOR VARIOUS DEPTHS OF COVER.

Cover	Anomaly	Maximum		Minimum	
		Position	Value	Position	Value
0	ΔZ	0·0	6308**	1·1	−2268**
0·1	ΔZ	0·1	4960	1·1	−1500
0·2	ΔZ	0·1	4100	1·3	−949
1·0	ΔZ	0·0	1451	3·5	−209
0	ΔH	0·0	3016**	1·0	−6677**
0·1	ΔH	−0·1	1944	0·9	−4900
0·2	ΔH	−0·3	1226	0·9	−4035
1·0	ΔH	−1·5	284	1·0	−1381

** In computing these anomalies the height of the instrument (4 feet) has been taken into account.

Table 4 shows the theoretical variation of the magnitude of the anomaly with the depth of cover and would serve, by the magnitude of the observed anomaly, to determine the depth of cover, provided the susceptibility were known or could be depended upon to remain constant. Two other features of interest in connection with this table are the fairly constant positions occupied by the maximum of the vertical and by the minimum of the horizontal intensity.

TRAVERSE II

Location.—This traverse was made along the road from Thetford North to Pontbriand, where the dyke is drift-covered. At chainage 890 (Fig. 21) there is an outcrop of quartzite, and about 250 feet from chainage 1,000, on a magnetic bearing of 70° east, an outcrop of serpentine. No sedimentary outcrops were definitely located on the traverse at the probable north boundary of the dyke, but it would be inferred, from outcrops to the east, that the boundary is to the south of chainage 1,900.

Instruments.—The dyke was traversed here with the Askania variometers, a Gurley dip needle, a Brunton compass to determine the declination anomaly, and also the Hotchkiss superdip, which measures anomalies in the total intensity. The anomalies in the dip (Fig. 22) were determined by direct measurement with the superdip, except that the anomaly at chainage 1,750 was computed from the Askania results.

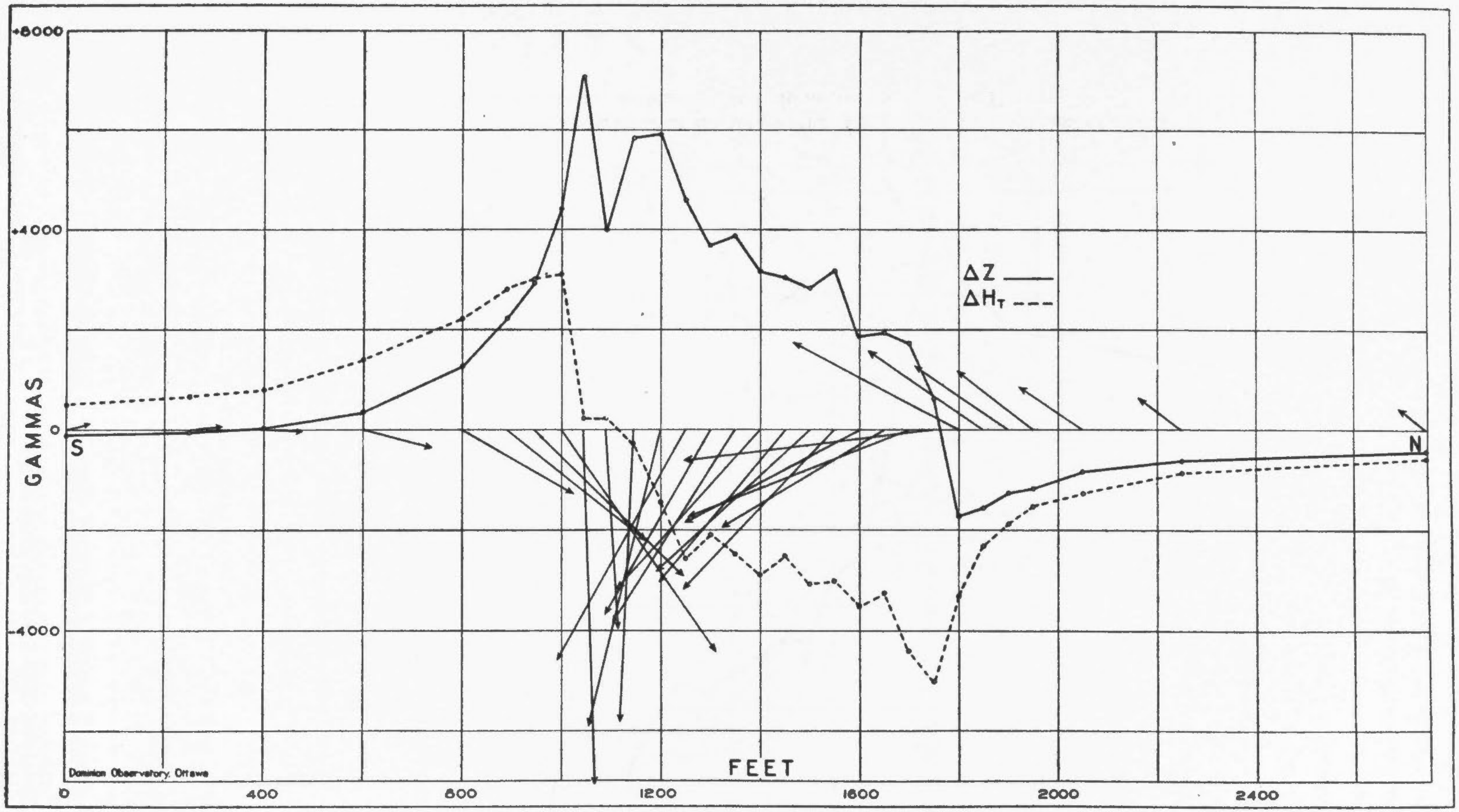

FIG. 21.—Magnetic profile of Pennington dyke at the intersection with the road from Thetford North to Pontbriand, showing anomalies in the vertical and horizontal intensities, and anomaly vectors (traverse II). Along this traverse the dyke is drift covered. It is inferred from the geology that it lies between limits of chainage 890 and 1900.

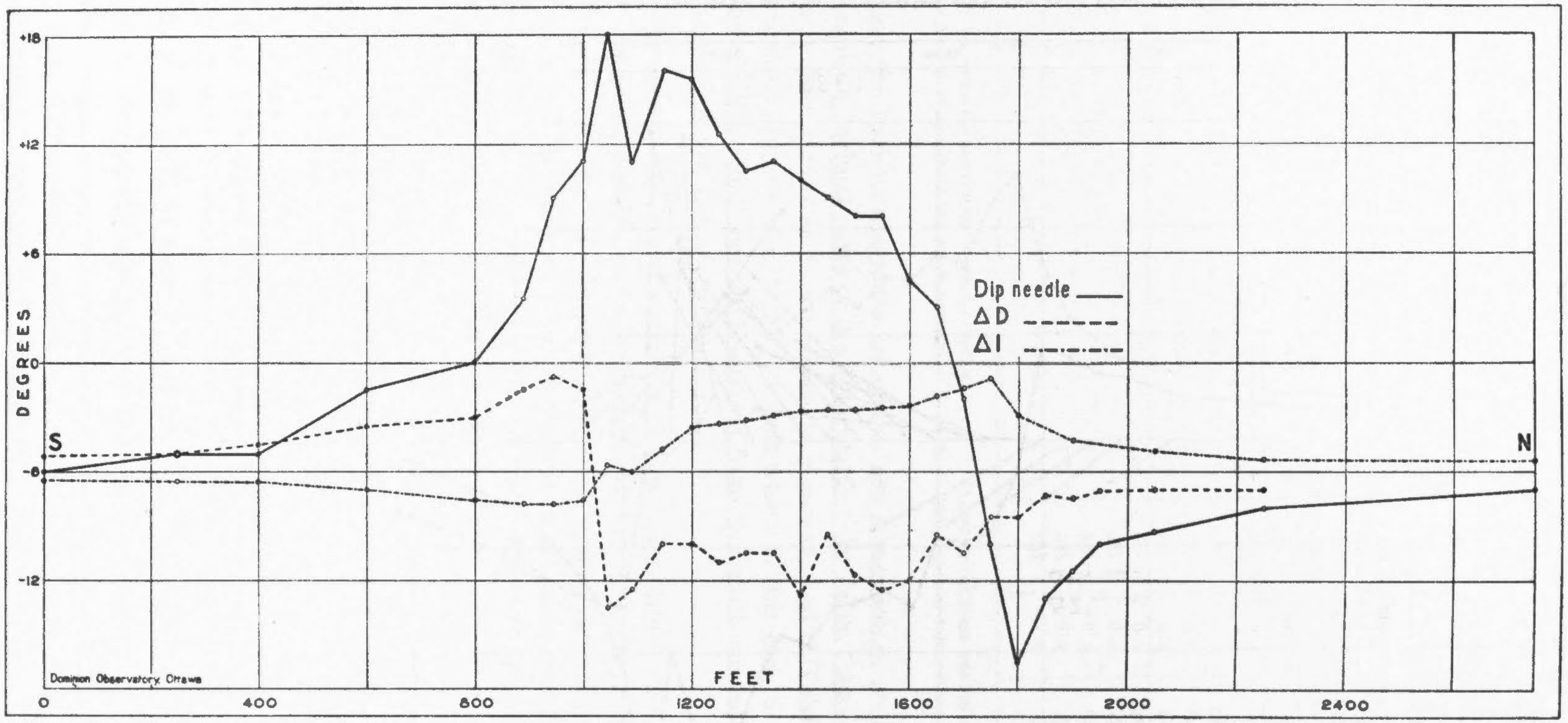

Fig. 22.—Magnetic profile of Pennington dyke at the intersection with the road from Thetford North to Pontbriand, showing dip needle, declination, and dip anomalies (traverse II).

Position of the dyke indicated by the results.—The results, particularly those plotted in Fig. 21, indicate that the dyke lies between chainages 1,000 and 1,800 (or perhaps 1,775) and that these points are not far from the south and north boundaries. By comparison with Fig. 18, it may be inferred that the dyke at traverse II lies at a depth of less than 200 feet, and it is of interest to note that the ratio of depth of intersection to dyke width bears the same ratio in the two cases. The inter-relation of the ΔZ and ΔH_T curves in Fig. 21, and the magnitude of the anomalies, suggest that the dyke is probably not more than 0·1 of its width below the surface or less than 70 feet. The results also indicate that the dip of the dyke is in the same direction and of about the same magnitude as at traverse I.

HOTCHKISS SUPERDIP*

Principle and adjustment.—A complete description of this instrument is given by Noel H. Stearn.[4] The principle of the superdip is indicated by Fig. 23. The magnet is mounted at its centre on a cylindrical agate bearing, and mounted on the same axis there is a light brass counter arm carrying a small weight, W, which can be adjusted in position along the arm. The angle, β, between the counter arm and the axis of the

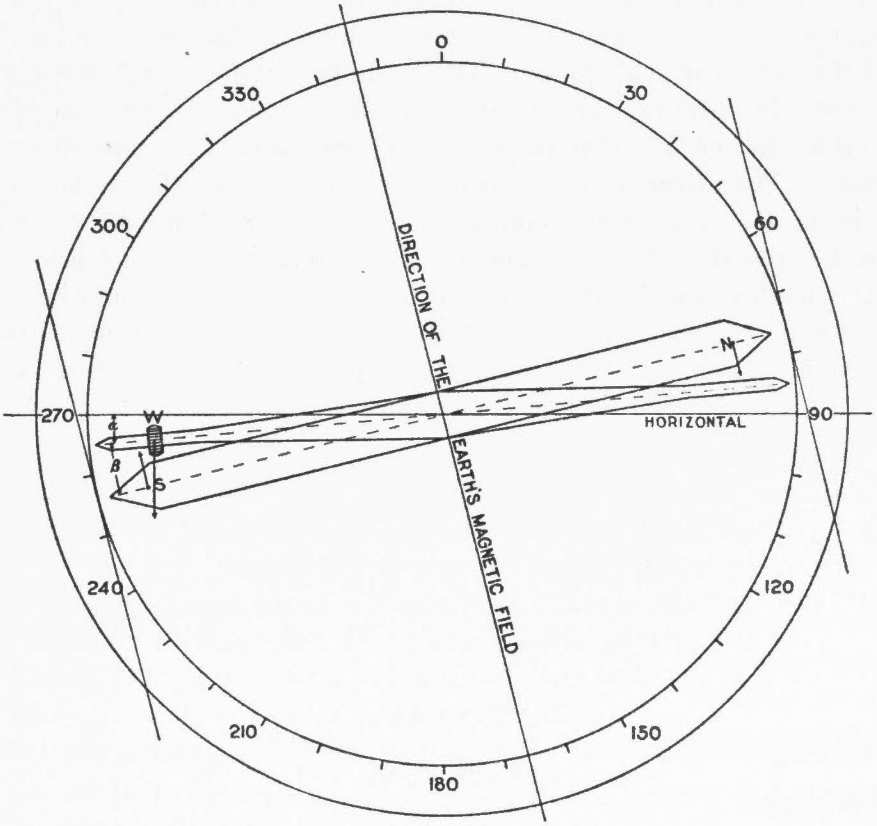

Fig. 23.—Illustrating the principle and setting of the Hotchkiss superdip.

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* One of these instruments was placed at the disposal of the Geological Survey for a few months through the courtesy of W. C. McBride, Inc., St. Louis, Mo.

[4] Noel H. Stearn. Practical Geomagnetic Exploration with the Hotchkiss Superdip. Tech. Pub. No. 370, A.I.M.E., New York meeting, February, 1931.

magnet can be set at any desired value. The system is placed in a cylindrical case with the axis of the magnet in the plane of the magnetic meridian. Agate knife edges are mounted in the case to act as a support for the magnet bearing. The position of the weight on the counter arm is adjusted until the axis of the magnet is in equilibrium in a position at right angles to the magnetic field with the north pole of the magnet towards north. The sensitivity can be adjusted to almost any desired value by altering the angle between the counter arm and the axis of the magnet. If this angle is made equal to the complement of the dip, the system is in equilibrium at any angle in the meridian plane, and theoretically the slightest change in the magnetic intensity will produce a rotation of 90 degrees bringing the magnet parallel to the earth's field with north pole down or up depending on whether the change is an increase or a decrease in the earth's field. In both cases the counter arm will lie in the vertical, with the weight above the axis of rotation in the first case and below it in the second. As such extreme sensitivity is not desirable, the counter arm is set at some angle differing from (usually less than) the complement of the dip, as indicated in Fig. 23. At traverse II, this angle was made equal to 9 degrees. As the normal dip was 76 degrees, the angle α, by which 9 degrees fell short of the complement of the normal dip, was 5 degrees.

Manner in which readings are taken.—When the instrument is taken from the place of adjustment to some other place where the intensity is different, the instrument will be deflected through some angle θ, say. This could be determined by allowing the needle to come to rest. In order to save time it is the usual practice to bring the north pole of the needle up to the zero mark at the top of the graduated circle and allow the system to swing freely. The extremity of the swing is the reading for the station at which the instrument is set up. The base or normal reading is obtained in a similar manner, and it can easily be seen that the deflection (difference between base and field station) obtained by this method will be approximately double that which would be obtained by allowing the system to come to rest. For this ratio to hold exactly, it would be necessary to correct for the damping of the swing, which could be readily determined by noting the reading of the magnet on its first return towards zero.

Results obtained with the superdip.—In Fig. 24, curve I shows the values resulting from measurements with Askania vertical, and horizontal magnetometers by means of formula (4). As these instruments and the auxiliary magnets were carefully standardized, it is believed that curve I represents very nearly the true values.

Curve II shows the values obtained by applying to the superdip readings the instrumental scale values obtained by scaling (for Σ which is the same as α defined above = 5 degrees) from figure 5 in Technical Publication No. 370[4].

Curve III represents for the superdip values that were deduced from the formula $\Delta T = \frac{Wl}{M} \sin \alpha \tan \theta$, where ΔT is the variation (from the normal) in the total intensity, W is the weight of the counter arm mass, l its lever arm, and M the moment of the magnet, and θ is the angle of deflection already defined.

Curve IV was obtained by using the formula $\Delta T = \frac{Wl \cos \theta_1}{M \sin A} - T_o$, where T_o is the value of the normal total intensity, θ_1 is the angle between the counter arm and the hor-

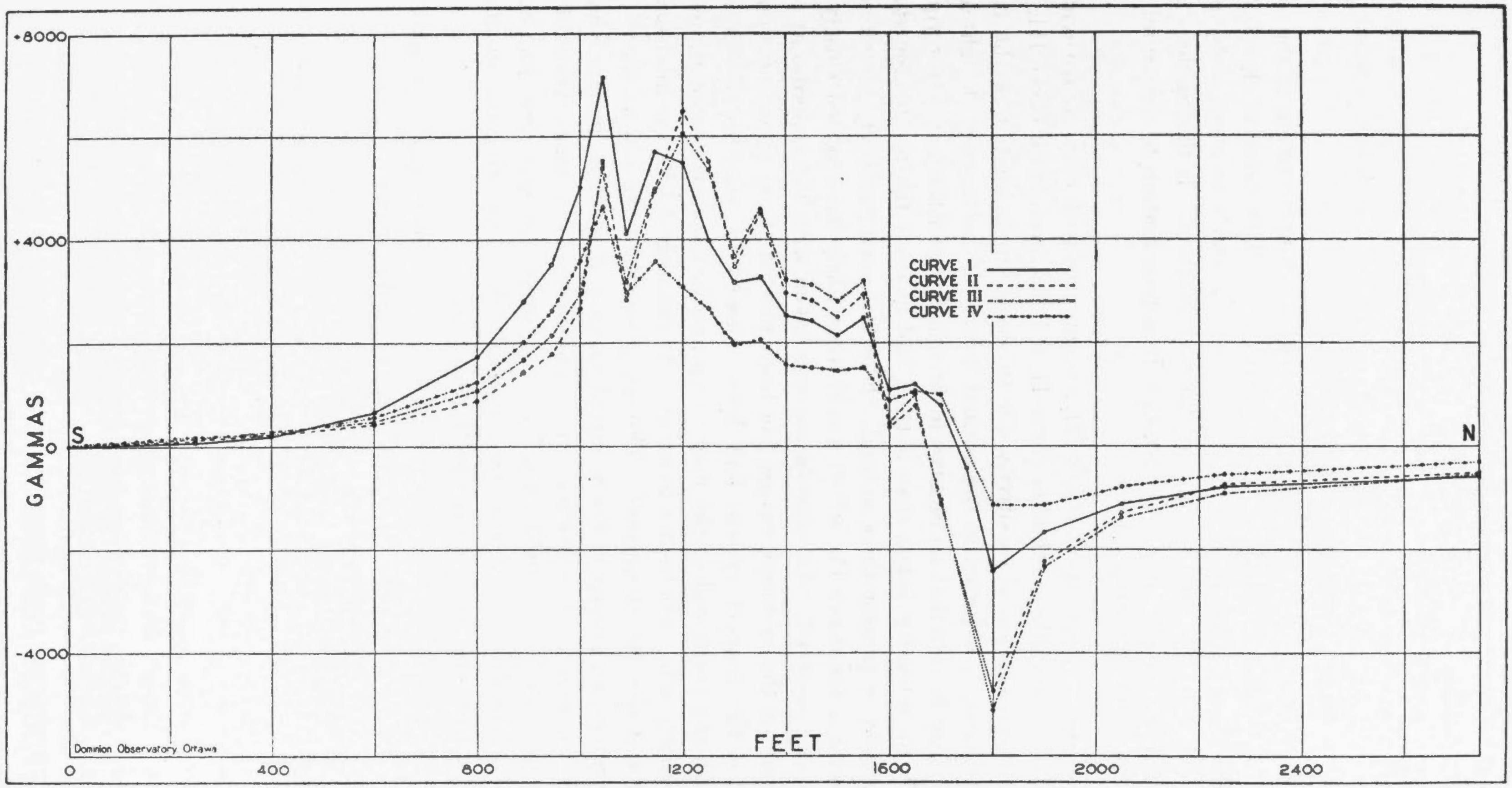

FIG. 24.—Magnetic profile of Pennington dyke at the intersection with the road from Thetford North to Pontbriand, showing anomalies in the total intensity as deduced from the measurements with Askania magnetometers (continuous line) and as computed by three different methods (broken lines) from the results obtained with the Hotchkiss superdip (traverse II).

izontal for equilibrium at the station, and A is (for the same condition) the angle between the axis of the magnet* and the direction of the magnetic field at the station. If Φ is the angle measured clockwise from the vertical (or the top of the scale) to the north end of the magnet, $\theta_1 = 90° - \Phi - \beta$ (in this case $\beta = 9°$), $A = 180° + \Phi - D$, where D is the scale reading at the station, when the counter weight is removed, and is equal to the dip plus 90 degrees.

For curve IV, Φ was obtained by merely dividing the observed swing at the station by 2. This of course makes no allowance for damping. The value of Φ should be obtained either by allowing the system to come to rest (or nearly to rest), or by noting the angular reading on the first return towards the zero position. If this angle is added to the swing and the sum divided by 2, a reasonable approximation to the equilibrium value of Φ would probably be obtained.

The discrepancies between curves II and III, as compared with curve I, are evidently due to the fact that neither the method of curve II, nor the formula for curve III, takes into consideration the variation of sensitivity due to change in inclination of the earth's field. If the instrument is adjusted in the normal field with the magnet at right angles to that field, then it can be seen that an increase in dip will decrease the magnetic torque for stations at which the intensity is less than normal and increase the torque for stations at which the intensity is greater than normal. Effect of such variations is taken into account in the formula for curve IV, which would most likely have agreed closely with curve I if Φ had been observed. An observation was taken with the superdip at chainage 1,750, but none of the deduced values has been plotted. It is apparent from the observation that if the magnet system had been allowed to come to rest it would have set itself with the north end of the magnet up and in the direction of the earth's field. This is precisely what was bound to occur. At chainage 1,750, the intensity was less than normal and the dip 81 degrees. The complement of the dip at that station was therefore 9 degrees, and equal to the adjusted value of β. So, no matter what the intensity might have been for this station, the equilibrium of the magnet would have been in the direction of the earth's field, with north pole up for intensity less than normal and north pole down for intensity greater than normal. For measuring the anomaly at this station, the instrument, as adjusted, was therefore useless.

It is thus apparent that, in commencing any work, the instrument should be so adjusted as to minimize effects due to variation in dip. For the very large anomalies of this traverse, it was made unnecessarily sensitive.

The curves of Fig. 30 are plotted from observations taken on different days by different observers. The usually small discrepancies between the two curves appear to be, as a rule, due to observation error, which for some of the stations may have included discrepancies possibly arising from failure to set up each instrument at precisely the same location. It would therefore appear that, when reasonable consideration is given to the adjustment of the sensitivity, the usual method of computing the anomaly will not

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* Strictly speaking there is taken here the negative direction of the axis, *i.e.* N to S. The ratio $\frac{Wl}{M}$ may be obtained by setting up at any station where the intensity is known.

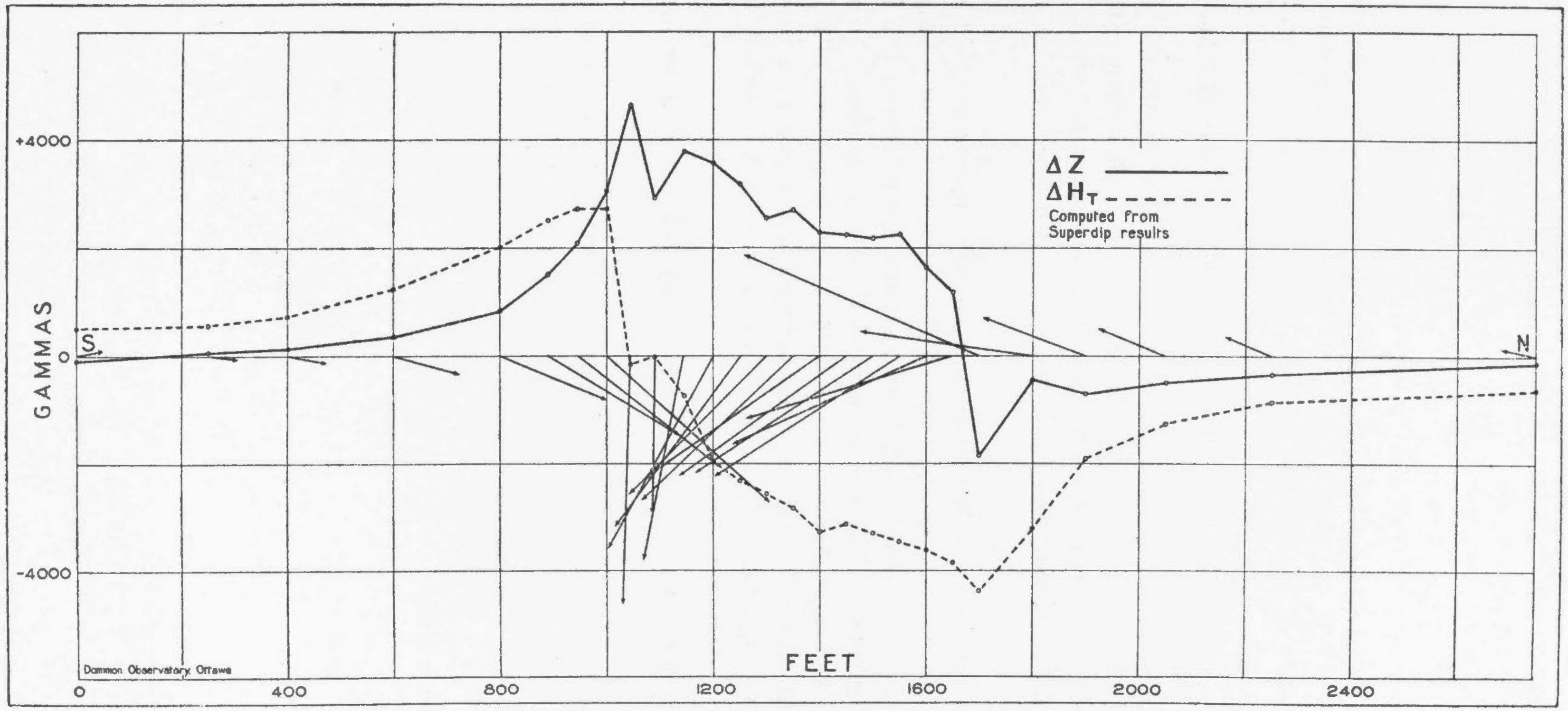

FIG. 25.—Magnetic profile of Pennington dyke at the intersection with the road from Thetford North to Pontbriand, showing anomalies in the vertical and horizontal intensities, and the anomaly vectors, computed from results with the Hotchkiss superdip (traverse II).

as a rule lead to serious error. It is only when the anomaly is comparatively large that such error might be anticipated, in which case it could be avoided by measurement of the dip and by application of the method indicated for curve IV.

The instrument is well adapted for field use, and is easy to operate and to read. Measurements with it can be taken with rapidity.

The data plotted in Fig. 25 were computed by means of formulae (1) and (2), using the formula for curve IV to obtain the value of T. The curves for ΔH and ΔZ and the intersection of the anomaly vectors are in fair agreement with those of Fig. 21.

LOCATION OF DYKE BY VARIOUS MAGNETIC INSTRUMENTS

Reference to Table 3 and the graphs shows that at shallow depths the dyke boundaries can be located, at least approximately, by any of the simple instruments—compass, dip needle, or dip circle. The dip needle locates the north boundary fairly accurately. Half way between the maximum and minimum values is in each case very nearly the centre of the dyke.

The boundaries can be more definitely located with instruments which measure the horizontal and the vertical components of the intensity. The maximum of the horizontal intensity is close to the south boundary, and the minimum is a little to the south of the north boundary. The minimum vertical intensity is closely associated with the north boundary, and in at least seven traverses where the position of this boundary was known, or could be safely inferred, the minimum was found at a point near the boundary, usually at or a little to the north. In two cases, it was slightly to the south of the boundary.

Anomaly vectors intersect at a point considerably below the upper surface of the dyke.

The above conclusions refer mostly to shallow depths, and are based on results obtained in places where the dyke is composed of the more magnetic type of serpentine.

SYMBOLS AND FORMULAE

H_o	normal	horizontal	intensity	(adopted	14,000)
Z_o	"	vertical	"	("	55,600)
T_o	"	total	"	("	57,300)
I_o	"	dip		("	76°)
D_o	"	declination		("	19°)

ΔH, ΔZ, etc., represent the anomalies in the various magnetic elements. $H = H_o + \Delta H$, $Z = Z_o + \Delta Z$, with similar expressions for the other elements. ΔH_T represents the magnetic anomaly along the traverse, κ magnetic susceptibility, η surface density of magnetic charge, η_T surface density of magnetic charge on upper surface of structure, η_s surface density of magnetic charge on sides of structure. θ has been used to represent the dip of the dyke and also the deflection of the superdip from the position of adjustment, and λ the strike of dyke measured from magnetic north.

$$H = T \cos I \qquad (1)$$

$$Z = T \sin I \qquad (2)$$

$$\Delta T = \Delta H \cos I_o + \Delta Z \sin I_o \qquad (3)$$

$$\Delta T = \sqrt{(H_o + \Delta H)^2 + (Z_o + \Delta Z)^2} - \sqrt{(H_o + Z_o)^2} \qquad (4)$$

$$\Delta H_T = (H_o + \Delta H) \cos \theta_2 - H_o \cos \theta_1 \qquad (5)$$

θ_1 is in this formula the angle between the traverse and normal magnetic north. θ_2 is the angle between the traverse and the direction of magnetic north at the station.

$$\Delta I = \tfrac{1}{2} \sin 2\,I \left(\frac{\Delta Z}{Z_o} - \frac{\Delta H}{H_o} \right) \quad \text{(6)}$$

$$\text{Tan}\,(I_o + \Delta I) = \frac{Z_o + \Delta Z}{H_o + \Delta H} \quad \text{(7)}$$

$$\left.\begin{aligned} \Delta Z &= 2\,\eta_T\,(\alpha_1 - \alpha_2) - 2\,(\alpha_1 - \alpha_2)\,\eta_S \cos\theta + 2\eta_S \sin\theta \log_e \frac{r_2}{r_1}, \\ \Delta H &= 2\eta_T \log_e \frac{r_2}{r_1} - 2\,(\alpha_1 - \alpha_2)\,\eta_S \sin\theta - 2\eta_S \cos\theta \log_e \frac{r_2}{r_1}, \\ \eta_T &= \kappa T \sin I_o = \kappa Z, \\ \eta_S &= \kappa T \sin\lambda \sin\,[180^\circ - (\theta + I_o)]. \end{aligned}\right\} \quad \text{(8)}$$

For the Pennington dyke $\theta = 60^\circ$, $\lambda = 70^\circ$, from which it follows that $\eta_S = \eta_T \times 0{\cdot}6728$. For definition of α_1, α_2, r_1, and r_2 see Fig. 26.

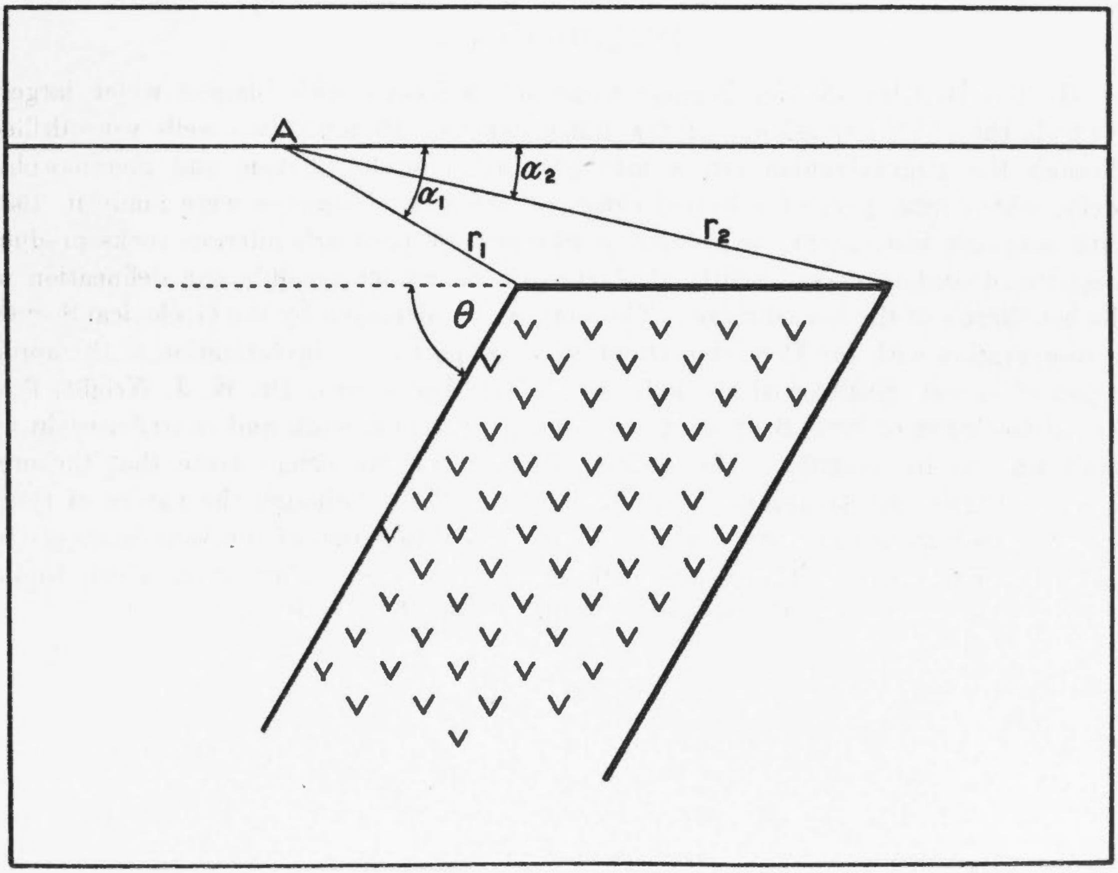

FIG. 26.—Illustrating factors used in the formulae for the theoretical magnetic effects of a uniformly magnetized dyke.

APPENDIX II—MAGNETOMETRIC SURVEYS OVER A BURIED "GRANITE" RIDGE NEAR MONCTON, NEW BRUNSWICK

By A. H. Miller and G. W. H. Norman

ABSTRACT.—Results of observations with magnetometers over this pre-Carboniferous ridge, which is associated with the occurrence of natural gas and oil, indicate that a systematic survey would most likely reveal in a general way the area in which pre-Carboniferous rocks approach the surface.

An account of the geology of the area, in so far as it has a bearing on the investigation, is included in the paper. A table is given showing the magnetic susceptibilities of some fifty rock specimens collected in the district. A section, which is devoted to the general features of the earth's magnetism, includes a table showing variations in the earth's field throughout the year.

The measurements were made by the authors with a Hotchkiss superdip, and Askania magnetometers. The results are shown graphically in seven profiles.

INTRODUCTION

In the Moncton district Pennsylvanian strata form a wide blanket which largely conceals the older formations. A few miles south of Moncton two wells were drilled through the Pennsylvanian strata into pre-Carboniferous igneous and metamorphic rocks, which form part of a buried ridge. Experimental surveys were made in 1932 with magnetic instruments to determine whether the pre-Carboniferous rocks produce magnetic disturbances sufficiently characteristic to render possible the delineation of the boundaries of the buried ridge. The work was undertaken by the Geological Survey in co-operation with the Dominion Observatory as part of an investigation of the application of various geophysical methods to geological problems. Dr. W. J. Wright, Provincial Geologist of New Brunswick, asisted with the field work and contributed in no small way to its progress. The results of these surveys demonstrate that the pre-Carboniferous rocks do produce magnetic disturbances. Although the nature of these disturbances may not in every case enable accurate delineation of the boundaries of the ridge, nevertheless it is thought that they should provide information which would indicate in a general way the area of concealed pre-Carboniferous rocks.

GEOLOGY

The rocks of the Moncton district (Fig. 27) belong to three main groups, pre-Carboniferous, Mississippian, and Pennsylvanian. The pre-Carboniferous and Mississippian rocks lie in folds having a regional northeasterly trend. These folds are truncated by erosion and are very largely buried by an extensive sheet of gently dipping Pennsylvanian strata. South of Moncton the Mississippian strata lie in a major syncline, partly broken by faults, the axis passing about two miles north of Hillsborough. Immediately north, and also south, of this syncline, ridges of pre-Carboniferous rocks occur. The southern ridge is well exposed along Caledonia mountain where the pre-Carboniferous rocks outcrop in a belt several miles wide. The northern ridge, suitably called the Moncton ridge, is for the most part concealed by the overlap of Pennsylvanian strata. The pre-Carboniferous rocks of this ridge occur in the two wells south of Moncton on the west side of the Petitcodiac river. Pre-Carboniferous rocks, probably forming part

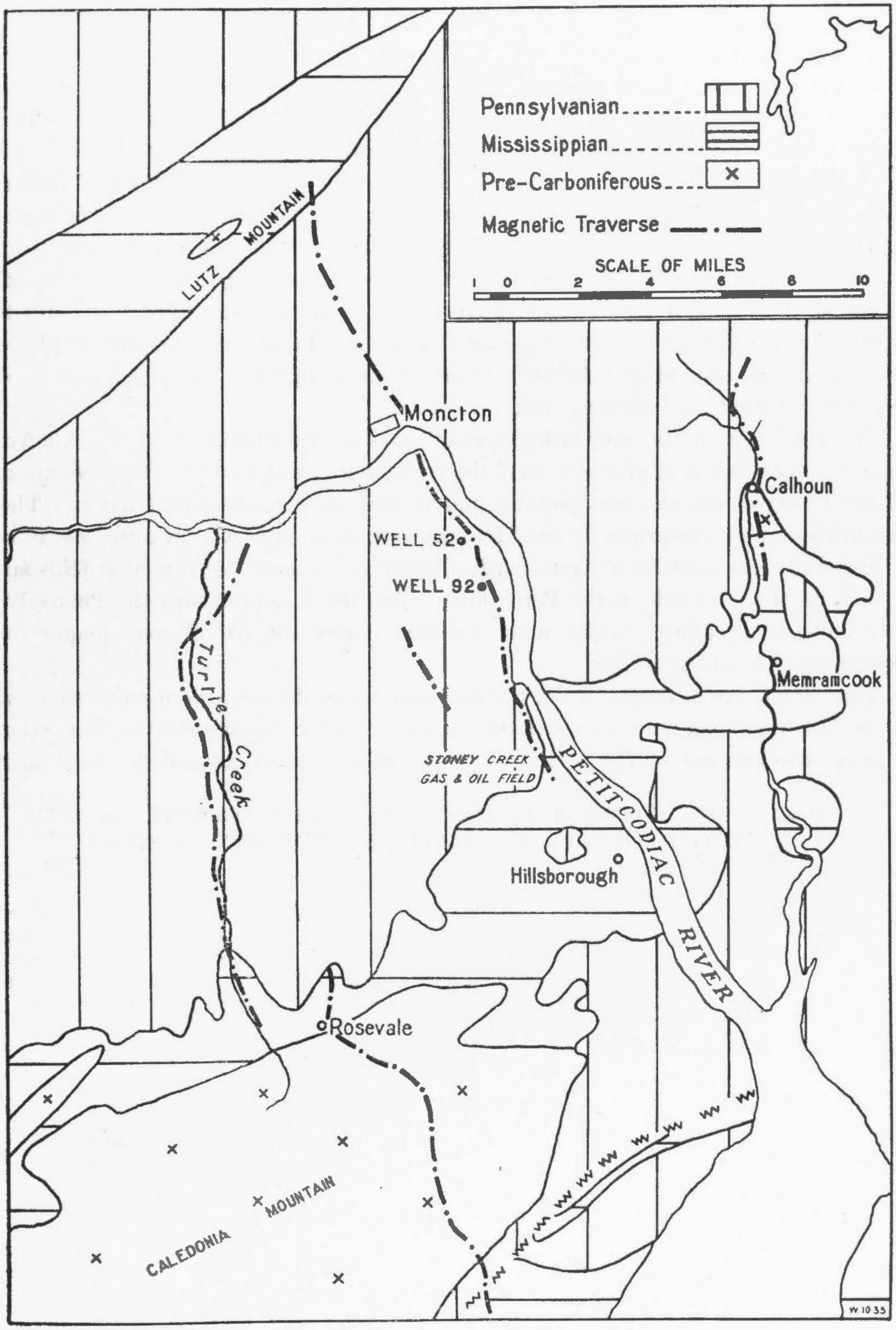

FIG. 27.—Location of magnetic traverses near Moncton, New Brunswick.

of the Moncton ridge, also outcrop on Memramcook river on the north side of the Mississippian syncline.

The pre-Carboniferous rocks at Caledonia mountain consist of a thick group of altered volcanic flows and tuffs, largely of basic composition, intruded by granite and diorite. The volcanic rocks have a well-developed cleavage which strikes generally about northeast and dips steeply to moderately to the north. Secondary chlorite, epidote, and white mica largely obliterate the original character of these rocks. Small thicknesses of phyllite, quartzite, and conglomerate are locally interbedded with the volcanic rocks, but the metamorphism masks the age-relation of the various strata and their structure.

The intrusive rocks form irregular sheets, which are aligned for the most part parallel to the regional cleavage of the volcanic rocks and also apparently dip to the northwest concordantly with the regional cleavage. The granite and diorite phases are about equally developed at Caledonia mountain and together underlie about one-third of the area of pre-Carboniferous rock.

The character of the pre-Carboniferous rocks of the Moncton ridge is known only at a few points, but it is probable that the rock groups which occur at Caledonia mountain are present here also but possibly not in the same relative proportion. The pre-Carboniferous rock exposures on the Memramcook river consist of granite, low in quartz but high in biotite and hornblende, with albite oligoclase as the principal feldspar. In the wells on the west side of the Petitcodiac river, the rocks beneath the Pennsylvanian strata consist of chlorite schist with included masses of titaniferous magnetite and ilmenite, diorite, and granite.

The percentage of magnetite in the different types of pre-Carboniferous rocks varies, as does also their magnetic susceptibility (table 5), which is apparently proportional to the magnetite content of the rock. The magnetite is most abundant in the intrusive

TABLE 5—SHOWING COMPARATIVE AND APPROXIMATE ABSOLUTE MAGNETIC SUSCEPTIBILITIES OF ROCKS COLLECTED IN MONCTON DISTRICT

Rock specimen	Number of samples tested	Deflection		Approximate magnetic susceptibility in units of 1 x 10^{-6} c.g.s.
		Range	Average	
Altered volcanics	12	0·1 – 0·5	0·29	67
Diorite	2	1·9 –30·0	16·0	3712
Sheared diorite	3	0·15– 0·3	0·23	53
Granite	4	0·05– 0·4	0·16	37
Sheared granite	6	0·05– 0·15	0·08	19
Granite (high in biotite and hornblende)	3	11·0 –13·0	11·8	2738
Green schists (doubtful origin)	7	0·1 – 0·7	0·3	70
Green schists (with included masses of Ilmenite)	1	....	19·0	4408
Manganese ore	1	....	0·5	116
Carboniferous sedimentary—				
Conglomerate	2	0·1 – 0·25	0·18	42
Sandstone	3	0·0 – 0·15	0·07	16
Shaly sandstone	2	0·05– 0·10	0·08	19
Oil shale	1	....	0·08	19

rocks and tends to be segregated with hornblende and biotite. The diorite has a high percentage of hornblende and an estimated magnetite content of nearly 1 per cent. Two types of granite, which are about equally prevalent, occur at Caledonia mountain. One type is composed of quartz and feldspar with few ferromagnesian minerals and only a small percentage of magnetite. The other type is low in quartz but contains about 20 per cent of biotite and hornblende and a percentage of magnetite approaching that of the diorite. Magnetite was not definitely recognized in the volcanic rocks, although many of these rocks contain as much as 5 per cent of "iron ores", which are present in very much smaller grains than in the diorite or granite. The "iron ores" of these rocks are largely hematite. Ilmenite, partly altered to leucoxene, is also present in thin sections of these rocks.

The Mississippian formations constitute a group of stratified rocks, which were deposited for the most part under continental conditions and are estimated to be at least 10,000 feet in thickness. They consist predominantly of red-coloured shale, sandstone, and conglomerate, but contain one thick group of grey sandstone and shale with bituminous shale interbeds.

After the deposition of the main group of Mississippian strata, the rocks were folded and eroded prior to the deposition of the Demoiselle formation, which has been assigned to the upper Windsor series of Mississippian age. This formation consists of red shale with argillaceous limestone interbeds and conglomerate.

The Pennsylvanian strata are structually conformable with the Demoiselle formation and are the most widespread rocks of the district. The basal Pennsylvanian rocks are principally grey to brown quartz pebble conglomerate, and are overlain in the vicinity of Moncton by red shale and sandstone. In well 1, three miles east of Moncton, they are 685 feet thick and it is probable that they do not exceed 1,000 feet in thickness anywhere in the Moncton basin.

The magnetic surveys described in the following pages were undertaken to test the feasibility of employing magnetic methods to detect the boundaries and to outline the extent of the Moncton ridge, which is concealed by the Pennsylvanian strata.

EARTH'S MAGNETISM

An acquaintance with the general features of the earth's magnerism[1],[2] provides a background which permits a better understanding of the results of the magnetic surveys. The earth acts as if it were itself a magnet. Its magnetic field is approximately that of a uniformly magnetized sphere, and it can be shown that the field outside the sphere is the same as that due to a small magnet placed at its centre. At the magnetic equator the forces are horizontal, but away from the equator become inclined and reach a vertical direction at those places on the earth's surface which are known as the magnetic poles.

It is of interest to note that, in approximate accord with theory, the intensity at the equator is just about half that at the pole. The horizontal and the vertical components

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[1] Daniel L. Hazard. The Earth's Magnetism. Special Publication No. 117, U.S. Coast and Geodetic Survey. 1925.

[2] H. Shaw, J. McG. Bruckshaw, and S. T. Ewing. Applied Geophysics, pp. 12–18, Board of Education, Science Museum, London. 1931.

of the magnetic force vary with the inclination. The horizontal component normally decreases while the vertical increases toward the poles. If the earth were a homogeneous mass and unaffected by outside conditions, its field would vary less from place to place than it actually does. Its field is complicated by lack of homogeneity in the crust and by other causes of extra-terrestrial origin. The lack of homogeneity produces either small regional anomalies, attributable to deep-seated causes, or local anomalies due to the diversity of the more superficial rocks. The local anomalies are often large and distinctive and furnish definite information regarding the character of the underlying rock. But the anomaly may be either so small, or differ in such a manner from one rock formation to another, that definite assignment of the cause of the anomaly is impossible.

Variations of the field with respect to time.—Apart from these variations over the surface of the earth, it is found that at any one place the magnetic elements are themselves continually changing, and in accurate magnetic surveying it is necessary to take account of these changes. They may be divided[3] into three main classes: (1), those which follow a regular periodicity—that is to say the variations are such that the elements after passing through a certain cycle return to their original values; (2), those which follow an orderly change which is in one direction for long intervals of time; (3), those of a more abnormal nature known as magnetic storms. The periodic variations include the well-defined diurnal variation and the less marked annual variation. In the second class we have the secular change, a gradual variation which in the course of a year represents a change that is by no means negligible. Magnetic storms are of a more erratic and irregular nature. Fortunately they are not sufficiently frequent to interfere seriously with magnetic surveys, but a severe storm may make accurate observation impossible and a moderate storm may render the results unreliable.

With the possible exception of the secular variation, which is not properly understood, the other disturbances can for the most part be attributed to radiation from the sun. The diurnal variation at any place depends upon the height of the sun above the horizon and, although possibly due in part to tidal effects of both the sun and moon, is probably, in the main, due to heating of the atmosphere by the sun, giving rise to atmospheric circulation which interacts with the earth's magnetic field to produce electric currents in the upper atmosphere. It is supposed that the magnetic effect of these currents is the cause of the diurnal variation.

Importance of correcting for the time variations.—In making a magnetic survey such as that described in this paper one is concerned, in making corrections for the variations, with the combined effect of all three time variations mentioned above. The largest and most troublesome are the magnetic storms.

During the year 1930, which was more than usually disturbed magnetically, the average range of the periodic part of the daily variation (the "diurnal inequality") was only 43 gammas for the horizontal intensity and 32 gammas for the vertical intensity. These were the variations[4] at Agincourt Magnetic Observatory near Toronto. At Abinger Magnetic Observatory, England, the variations were smaller, the corresponding values being 31 gammas and 25 gammas.

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[3] W. F. G. Swann. Terrestrial Magnetism. Encyclopaedia Britannica, 14th edition. 21: 959–970.

[4] J. Patterson. Results of Meteorological and Magnetic Observations, 1930, p. 37.

TABLE 6—RANGES OF EXTREME VALUES OF MAGNETIC ELEMENTS FOR THE YEAR 1930 AT ABINGER MAGNETIC OBSERVATORY, TOGETHER WITH THE MONTHLY EXTREMES AT AGINCOURT

Month	Ranges in declination in minutes of arc					Ranges in horizontal intensity in gammas							Ranges in vertical intensity in gammas						
	Average daily range	Greatest range for any day of month	Number of days on which the range exceeded 30′	Number of days on which the range exceeded 60′	Extreme range for month—Abinger	Average daily range	Greatest range for any day of month	Number of days on which the range exceeded 100 gammas	Number of days on which the range exceeded 150 gammas	Number of days on which the range exceeded 300 gammas	Extreme range for month—Abinger	Extreme range for for month—Agincourt	Average daily range	Greatest range for any day of month	Number of days on which the range exceeded 100 gammas	Number of days on which the range exceeded 150 gammas	Number of days on which the range exceeded 300 gammas	Extreme range for month—Abinger	Extreme range for month—Agincourt
January........	13·1	31·7	1	0	33·4	59	125	3	0	0	171	144	29	79	0	0	0	84	78
February.......	17·6	49·4	2	0	50·9	76	182	5	1	0	189	423	40	107	1	0	0	129	190
March..........	17·4	36·0	1	0	36·0	92	174	13	2	0	236	490	47	122	1	0	0	122	205
April...........	20·5	30·3	1	0	40·4	116	235	17	7	0	264	486	64	117	3	0	0	135	633
May...........	18·5	34·7	3	0	37·8	110	234	19	4	0	285	423	64	171	5	1	0	211	485
June............	15·8	32·2	1	0	33·4	111	236	18	6	0	293	684	54	94	0	0	0	100	736
July............	14·2	31·0	1	0	31·0	97	202	13	3	0	206	399	49	134	2	0	0	162	318
August.........	17·4	36·8	1	0	38·7	102	209	11	6	0	254	405	51	125	1	0	0	125	424
September.....	18·6	46·4	3	0	48·1	95	202	14	4	0	270	501	50	125	3	0	0	190	588
October........	18·8	52·4	2	0	52·9	93	192	15	5	0	250	560	47	195	2	1	0	245	492
November.....	12·1	32·7	1	0	34·5	65	179	4	2	0	189	327	33	114	2	0	0	138	230
December......	12·2	46·3	3	0	49·4	51	227	2	1	0	227	409	32	233	1	1	0	270	301
Average......	16·4	38·3	1·7	0	40·5	89	200	11·2	3·4	0	232	438	47	135	1·8	0·3	0	159	390

During the ten years 1920 to 1930, the horizontal intensity decreased at Agincourt at the rate of 32 gammas per year, and the vertical intensity decreased at the rate of 103 gammas per year.

Magnetic storms may begin abruptly, usually at the same time all over the earth, and their effects may last for several days. The amplitude of the fluctuations is greater in high latitudes than in equatorial regions. A magnetic storm has been defined as a disturbance which produces either a range of 30 minutes of arc in the declination or a variation of 150 gammas in either the vertical or the horizontal intensity. A great storm is one for which these ranges are exactly doubled, that is to say, 60 minutes and 300 gammas. According to this definition, H. W. Newton of the Royal Observatory, Greenwich, finds that there have been in the ten years 1923 to 1932, at Abinger, 106 storms, 12 of which fall into the classification of great storms, on the average one storm per month and one great storm per year. In this period, however, all of the great storms but one (in May 1932) occurred between the years 1926 and 1929, corresponding as a matter of fact to a time of sunspot maximum. During 1930 there were 23 magnetic storms, but no great storms.

Table 6 gives an idea of the variations in the magnetic elements that may be met with in the course of a day's work. As the ranges (differences between the highest and lowest values for the day) in the table are for a complete day of 24 hours, the indicated changes will be greater than those that are likely to occur during the nine or ten working hours. With the exception of the data for Agincourt, this table has been compiled from Table IV of the *Results of Magnetic Observations* made at Abinger Magnetic Station in the year 1930*, which gives the daily mean and extreme values for each day of the year. Extreme ranges in the horizontal and the vertical intensities for the month are given for both Abinger and Agincourt in Table 6. It is apparent that Agincourt was more disturbed than Abinger. The extreme ranges throughout the whole year were for H at Agincourt 873 gammas, at Abinger 311 gammas; for Z at Agincourt 926 gammas, at Abinger 345 gammas; and for declination at Abinger 1° 05ʹ.3. The table shows the necessity, in accurate work, of keeping track of the variations that occur in the elements during the working hours. If the work is near a magnetic observatory, the corrections may be obtained from that observatory. As there are only two such observatories in Canada, this will not usually be possible in this country. Either a base station must be established, equipped with a separate observer and instrument or instruments (depending on the elements that are measured in the field work), or else return to a selected base station (or temporary base stations) must be made sufficiently frequently, with the field instrument or instruments as the case may be, in order that the changes may be followed. The table also shows that the vertical intensity variations are only about half as great as the horizontal, a rather fortunate circumstance, as the vertical instrument is the one for which there is the greater use.

SURVEYS

A preliminary traverse was made with a dip needle in the vicinity of Memramcook to determine the approximate magnitude of the magnetic anomalies over the pre-Carboniferous rocks which outcrop there. A deflection of the needle of nearly 4 degrees,

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* Observations made at the Royal Observatory, Greenwich, in the Year 1930, Section D.

equivalent to somewhat less than 1,000 gammas, was observed over pre-Carboniferous granite after passing the boundary of the granite and Mississippian sedimentary rocks. It was concluded that important information might be obtained from an investigation of such anomalies with more delicate instruments. Observations were accordingly begun with Askania magnetometers and a Hotchkiss superdip. The scale value of the Askania horizontal magnetometer was 22 gammas and that of the vertical 55. The sensitivity of the Hotchkiss superdip was adjusted to give a value of 20 gammas to one division on the scale. In order to obtain this sensitivity in the Moncton district, where the normal inclination of the earth's magnetic field is about 75 degrees,* the angle between the counterarm and the axis of the magnet was set at 13 degrees.

The traverses were made principally along roads, but at Calhoun the traverse in part followed the railroad. The stations were placed 300 to 400 feet from the roads to avoid proximity to buried metal, fences, and telephone or power lines, although the disturbances produced by these were quite local; even the disturbance produced by the railway at Calhoun disappeared entirely at a distance of 300 feet. The stations were spaced mostly 500 feet apart where the changes in magnetic intensity were rapid, and a few were spaced even closer. Where the magnetic intensity proved to be uniform over long stretches, the stations were spaced 1,000 or 1,500 feet apart or even further, depending on the amount of detail desired.

Selection of reference point.—All observations along the traverses were referred to the station at the south end of the main traverse near Weldon brook, where there appears to be little or no magnetic disturbance. It was assumed that the magnetic elements at this station were normal. The station is well within the Mississippian sedimentary basin, and is approximately equidistant from the Caledonia and Moncton ridges of pre-Carboniferous rocks.

Corrections applied for diurnal and other variations.—During the course of the work G. P. Hatton took observations with two Askania instruments at the camp base, established for the purpose of keeping a record of diurnal and other variations. In addition, observations were taken at the camp base, at least twice daily, with all the instruments employed on the traverses. It was the regular practice with the superdip to establish temporary bases in the vicinity of each day's work, where readings were repeated at intervals throughout the day. This was also done on some days with the Askania instruments. As the regular observations with the camp instruments did not show any large abnormal variations throughout the course of the work, it is considered that, in view of the magnitude of the observed anomalies, the field readings were sufficiently corrected for variation in the earth's normal field by means of the readings taken with the field instruments at the temporary base stations and at camp.

All readings were corrected for temperature and for the normal variation of the earth's field per mile of latitude and longitude. The values for the normal variations were supplied by C. A. French of the magnetic division of the Dominion Observatory. These values show that in the vicinity of Moncton for each mile increase in latitude the vertical intensity (Z) increases by 6·2 gammas, the horizontal intensity (H) decreases

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* According to observations of the Dominion Observatory, the total intensity at Moncton in 1932 was 56,793 gammas, and the dip 74° 43′.

by 7·7 gammas, and the total intensity (T) increases by 4·0 gammas. For each mile increase in longitude, Z increases by 5·2 gammas, H decreases by 2·7 gammas, and T increases by 4·3 gammas.

Magnetic susceptibilities of the rocks.—During the course of the work, specimens of the various types of both sedimentary and igneous rocks of the district were collected and compared for magnetic susceptibility by determining the deflections which they produced when they were held near one of the Askania (horizontal) magnetometers. Only pre-Carbonifreous rocks exhibited marked magnetic qualities; the sedimentary rocks were only slightly magnetic.

In Table 5 are given the deflections that were produced on the horizontal magnetometer by the various rocks specimens. To obtain the susceptibility in c.g.s. units, the deflections have been multiplied, in the last column, by 232×10^{-6}. This relation between the deflections and the susceptibilities is based on a standardization of the instrument by a method described by J. G. Koenigsberger[5]. For relative determinations, this simple and rapid method is probably sufficiently accurate for the usual requirements in the field. As a matter of fact, the variation in susceptibility between individual specimens of apparently the same rock is often so great that no especial precision of measurement would, as a rule, appear to be necessary. The absolute values in Table 5, although apparently of the right order of magnitude, can hardly be expected to be any more than merely approximate.

DISCUSSION OF RESULTS

Probable error.—From repetitions of observations in the Moncton district and elsewhere, it is estimated that the probable error of an observation is from 10 to 15 gammas. It is not likely that any observation is in error by as much as 50 gammas.

Comparison of instrumental results.—Fig. 30 shows the values of the anomalies in the total intensity measured by the superdip and as computed from the results of the measurements with the Askania horizontal and vertical magnetometers. The values for the Askania observations were computed by use of the formula $\Delta T = \Delta H \cos I + \Delta Z \sin I$, where I is the angle of dip of the earth's magnetic field, ΔT the total intensity anomaly, and ΔH and ΔZ are the horizontal and vertical intensity anomalies.

Anomaly vectors and magnetic poles.—The arrows (Fig. 28, 29, 33, and 34), or anomaly vectors, indicate the direction and magnitude of the magnetic disturbance in the plane of the magnetic meridian at each station. As the traverses are approximately in the direction of magnetic north and as there can hardly be large anomalies in the declination, the vectors represent approximately the direction and magnitude of the anomalies in the vertical plane of the traverse. They are obtained by simple vector addition of the anomalies in the vertical and horizontal intensities. At the two places (Fig. 29) where the magnetic field is most disturbed along the main traverse, very definite intersections of the vectors occur. These points may be taken to indicate the positions of south poles. To determine their precise positions, further work, including the measurement of the

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[5] J. G. Köenigsberger. Method for Measuring the Susceptibility of Rocks. Terrestrial Magnetism and Atmospheric Electricity, Vol. 34, No. 3, pp. 209–214. September, 1929.

declination anomalies, would be necessary. In any event, undue importance should not be attached to these poles or intersections. Their significance may be more apparent than real. The direction of the vectors obviously depends on the adopted normal intensity. As shown in Appendix I and as illustrated by Fig. 20, such intersections of anomaly vectors may have no inherent physical significance, for they may arise from distribution of charge confined solely to the surface of the structure.

Two north magnetic poles, weaker than the south poles, are indicated, one to the south of well 84 and the other just south of the Petitcodiac river (Fig. 29). The positions of these north poles correspond to the intersections of the vectors in their reverse directions.

Assuming that the normal adopted for the vertical is nearly correct, the fact that, practically speaking, only south poles were found is an indication that the magnetization is induced by the earth's field, particularly as the intensity of magnetization appears to be in accord with this supposition. The corresponding north poles are probably at great depths, although it is not unlikely that further surveys might reveal the presence of strong north poles near the surface.

Intersections of vectors occur at points approximately vertically below the stations of highest anomaly in the vertical intensity, and although their depths vary considerably with the different traverses they do occur at a depth of about 2,000 feet on the main traverse, or about 1,500 feet below the upper surface of the pre-Carboniferous rocks. These intersections are associated with vertical intensity anomalies of about 500 gammas. If we suppose the anomalies to vary inversely as the square of the depth, then an intersection at a depth of 6,000 feet (2,000 × 3), equivalent to cover of 4,500 feet, would produce an anomaly of 55 gammas $\frac{(500)}{3^2}$. An anomaly of 30 gammas would require a depth of cover of about 6,500 feet. It is thus apparent why only small anomalies are found within the major Mississippian syncline, where the depth to the pre-Carboniferous may well be as much as 10,000 feet.

Calhoun traverse.—This traverse, through Calhoun (Fig. 28) was made along the road and the railroad to the east of Memramcook river. Steeply dipping Mississippian strata, tilted to an angle of 80 degrees at their contact with pre-Carboniferous granite, underlie the first mile of this traverse. Whether the contact dips as steeply as the adjacent sediments and whether the steep dip persists with depth cannot be determined, although both these conditions probably exist. The granite is exposed along the traverse for nearly a mile and a half south from Calhoun. North of Calhoun the Pennsylvanian strata conceal the older rocks. The geological conditions beneath the Pennsylvanian rocks are unknown.

Fig. 28 shows the anomalies produced by the pre-Carboniferous rocks along the traverse. The magnetic intensity remains uniform over the Mississippian rocks but increases rapidly to a maximum near the south boundary of the pre-Carboniferous granite. The horizontal component H reaches a maximum over the south boundary, while the vertical component Z reaches a mamimum immediately after the boundary is crossed. The traverse was extended with the superdip two miles to the north of the most northerly point indicated in the figure. The fact that throughout this distance only quite small anomalies were detected suggests that the north boundary of the pre-Carboniferous rocks was crossed near the second station south of the most northerly station shown in the figure.

Main traverse.—This traverse (Fig. 29 and 30) was made along the main road on the west side of the Petitcodiac river between Moncton and Hillsborough. North of the Petitcodiac river, the traverse was extended through Moncton and along the McLoughlin road as far as Lutz mountain with the Askania instrument, but the stations in this section of the traverse were a mile or more apart.

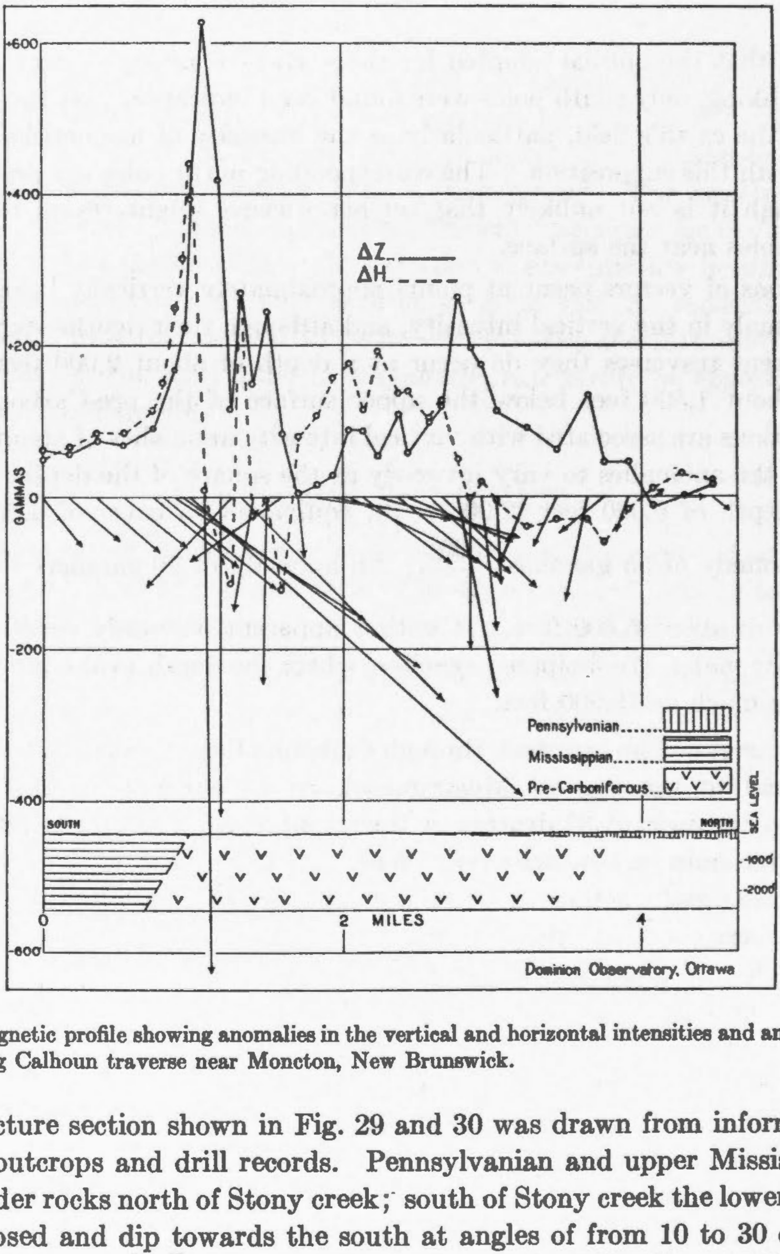

Fig. 28.—Magnetic profile showing anomalies in the vertical and horizontal intensities and anomaly vectors along Calhoun traverse near Moncton, New Brunswick.

The structure section shown in Fig. 29 and 30 was drawn from information derived from surface outcrops and drill records. Pennsylvanian and upper Mississippian strata blanket the older rocks north of Stony creek; south of Stony creek the lower Mississippian rocks are exposed and dip towards the south at angles of from 10 to 30 degrees. The pre-Carboniferous rocks of the Moncton ridge occur in wells 52 and 92 at a depth of about 355 feet, but neither the position nor the character of the southern contact be-

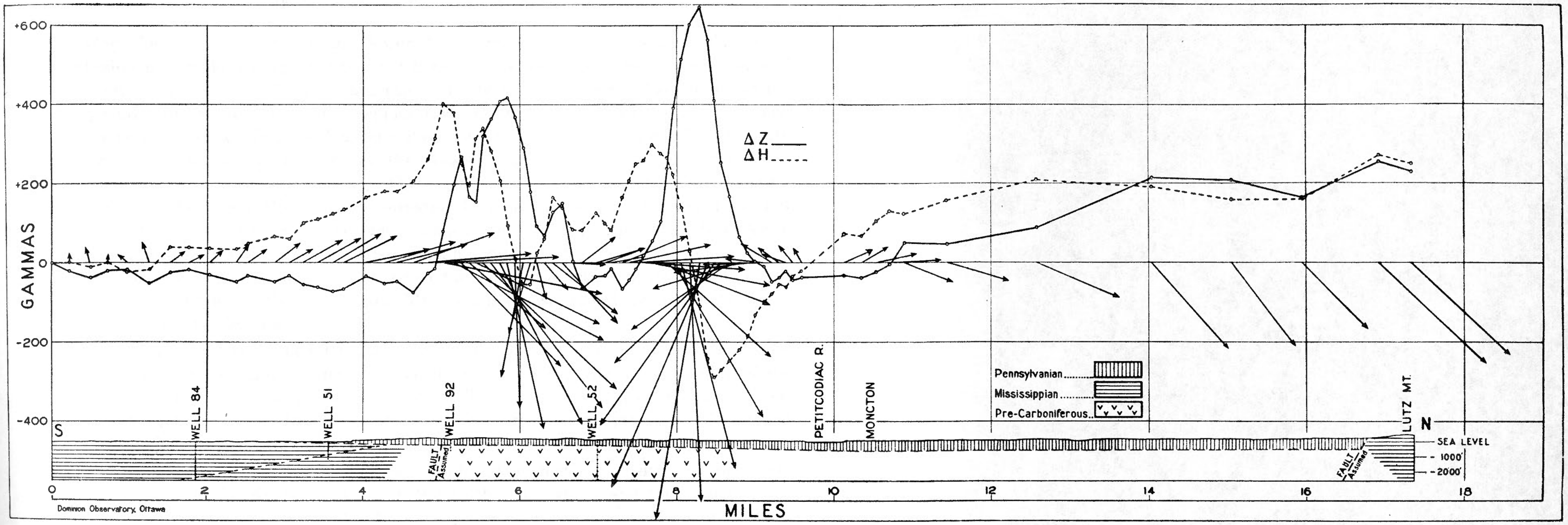

Fig. 29.—Magnetic profile showing anomalies in the vertical and horizontal intensities and anomaly vectors along the main traverse near Moncton, New Brunswick.

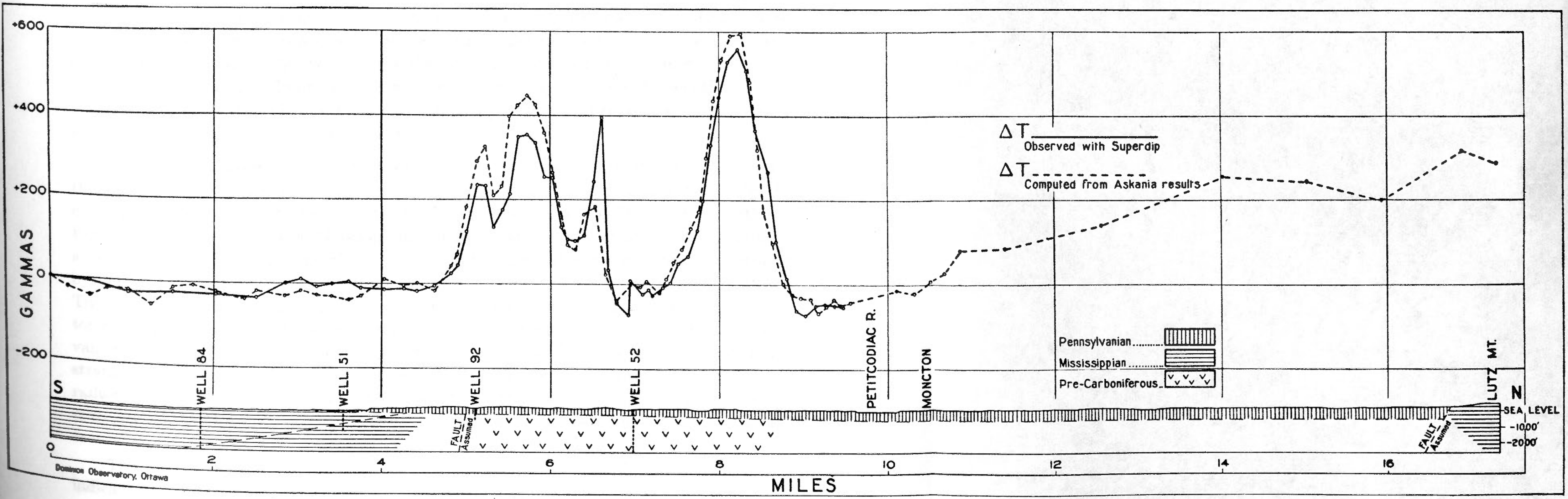

Fig. 30.—Magnetic profile showing anomalies in the total intensity measured with the Hotchkiss superdip along the main traverse near Moncton, New Brunswick, and as computed from results with Askania magnetometers. The continuous line shows the results obtained with the superdip. No observations were taken with this instrument along that part of the traverse lying to the north of Petitcodiac river.

tween the pre-Carboniferous and lower Mississippian rocks is known. The lower Mississippian rocks are reported to occur below the Pennsylvanian rocks in another well (about a mile east of well 92) at a depth of 310 feet. As the concealed contact of the pre-Carboniferous and lower Mississippian rocks must pass between these two wells and as it probably strikes in a northeasterly direction, it should pass a short distance south of well 92. On the structure section the Mississippian strata are shown faulted down against the pre-Carboniferous rocks. This fault is assumed to account for the apparent thinness of the lowest Mississippian formation here, as disclosed by the well logs; but this may be explained equally well by overlap of the younger formation. In order to account for the thickness of the Mississippian strata south of the Moncton ridge, it would seem necessary to suppose that the contact is steep, whether or not a fault occurs. Contacts of the pre-Carboniferous and Mississippian rocks elsewhere in the Maritime Provinces are usually steep.

Well 52, and well 1 which lies three miles east of Moncton, furnish the only information available regarding the pre-Pennsylvanian rocks along the northern part of the traverse to Lutz mountain. Samples from well 1, taken below a depth of 685 feet, indicate that the lower rocks are probably pre-Carboniferous granite. Diorite and Mississippian conglomerate are exposed at Lutz mountain.

The traverses (Fig. 29 and 30) show that the magnetic intensity remains fairly uniform over the Mississippian strata to the south of the ridge, and that anomalies of up to about 600 gammas occur over the pre-Carboniferous rocks. As the south boundary of the ridge is approached from the south, an anomaly in the horizontal intensity is apparent, and the south boundary of the pre-Carboniferous rocks is in fact indicated by the maximum of the horizontal component a short distance south of well 92, where it is inferred to lie from geological evidence. Additional detailed traverses are required on the northern side of the ridge before definite inferences regarding the rocks can be drawn, but the northern limit of the high vertical anomaly suggests the location of the north boundary of the ridge, although this anomaly might well be due to an intrusion in the pre-Carboniferous of more magnetic rock.

Turtle Creek traverse.—This traverse (Fig. 31) was made with the superdip along the road beside Turtle creek, from the Petitcodiac river to Caledonia mountain. Gently dipping Pennsylvanian strata conceal the lower rocks north of Berryton; south of Berryton the traverse crosses Mississippian rocks, which form part of the south limb of a synclinal structure. The northern limb of this synclinal structure, possibly broken by faulting, probably lies between Berryton and Turtle Creek railway station. North of Turtle Creek railway station it is possible that either a westerly continuation of the Moncton ridge, or an anticlinal structure in the Mississippian rock, occurs beneath the Pennsylvanian rocks, which are (here) about 1,000 feet thick. The thickness of the Mississippian strata along the section of the traverse between Caledonia mountain and Turtle Creek railway station is probably considerable, as all the Mississippian formations are apparently present at Berryton, where there total thickness is estimated to be at least 10,000 feet.

The lack of pronounced anomalies along this traverse is striking. It appears to indicate that the pre-Carboniferous rocks are buried beneath a thick cover of Mississippian

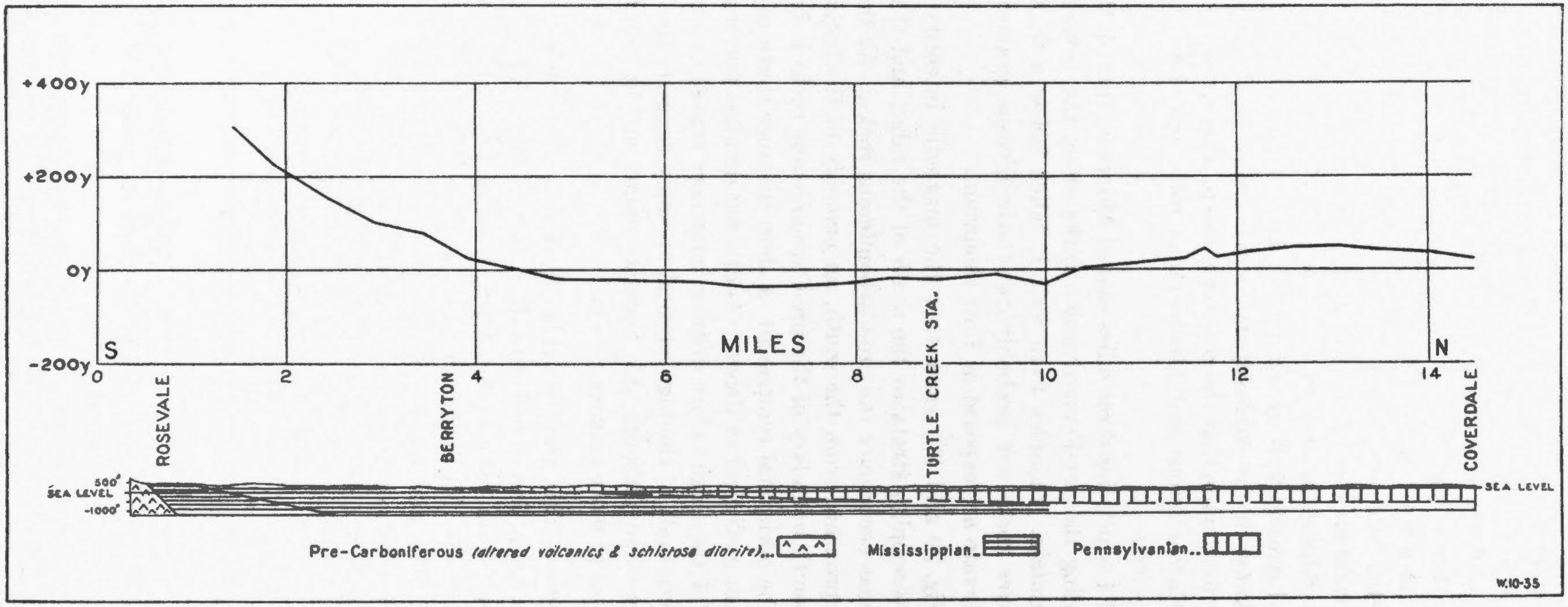

Fig. 31.—Magnetic profile showing anomalies in the total intensity as determined with the superdip along the Turtle Creek traverse near Moncton, New Brunswick.

strata. The stations on this traverse were spaced half a mile apart. Even if the stations had been spaced closer together, it is very unlikely that a different type of curve would have been obtained. North of Turtle Creek railway station, the intensity increases to a maximum but exceeds the lowest value on the curve by only 85 gammas. This suggests that, at the place where this maximum was observed, the pre-Carboniferous rocks occur at considerable depth, or else that they are less magnetic.

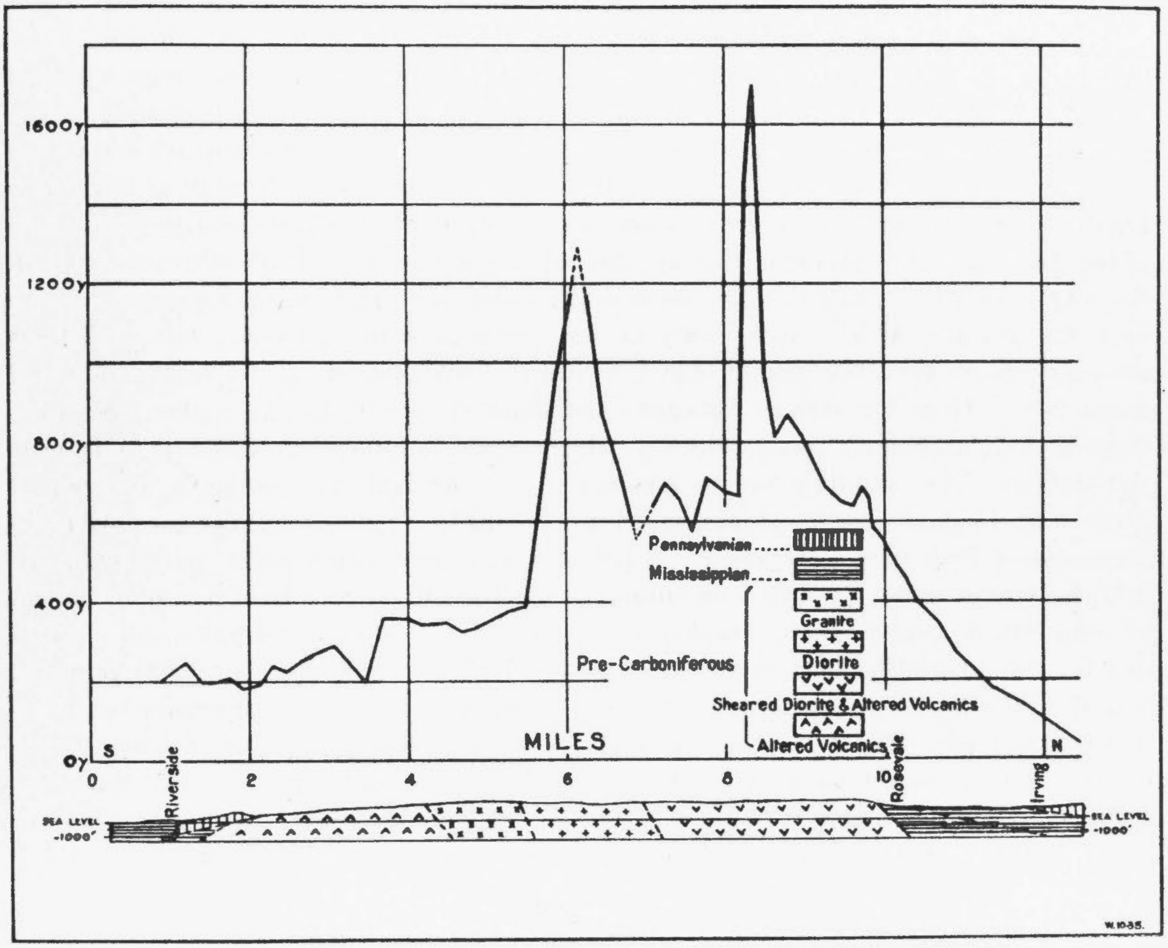

FIG. 32.—Magnetic profile showing anomalies in the total intensity as determined with the superdip along the Caledonia Mountain traverse near Moncton, New Brunswick.

Caledonia traverse.—This traverse (Fig. 32) was made with the superdip along the Caledonia road (across Caledonia mountain), from Rosevale to Riverside. The Mississippian and pre-Carboniferous rocks are exposed along this traverse, except for a short distance on the south side of Caledonia mountain where Pennsylvanian strata overlap pre-Carboniferous rocks. The contact of pre-Carboniferous with Mississippian rocks on the north side of Caledonia mountain probably dips to the north at an angle of at least 45 degrees, since a well over 2,000 feet deep and a little less than half a mile north of the mountain failed to reach the pre-Carboniferous rocks. The contact of pre-Carboniferous with Pennsylvanian rocks on the south side of Caledonia mountain dips more gently. The pre-Carboniferous rocks in the structure section (Fig. 32) are divided into four groups. The group boundaries as shown on the section are only approximately correct, since they are based on the extension of the contacts across the Caledonia road from streams (where the rocks are exposed) on either side of the road. On the north side of Caledonia mountain the pre-Carboniferous rocks consist of chlorite schist with intrusions of sheared diorite, but on account of the lack of sufficient exposures these rocks were not differentiated.

This traverse indicates clearly that the various types of pre-Carboniferous rocks differ considerably in magnetic character. The volcanic rocks on the south side of the mountain are only slightly more magnetic than the Carboniferous sedimentary rocks, and their contact is not well defined by the curve. This may be partly explained by the gentle dip of the contact. The results for the first three stations at the south end of the traverse show a small anomaly, which is apparently associated with the fault at Riverside. Farther east, pre-Carboniferous rocks are brought up to the surface along the south side of this fault, and it is probable that an upward movement of pre-Carboniferous rocks on the south side of the fault has also occurred at Riverside. Only a small anomaly occurs over the granite, which, here, contains few ferromagnesian minerals, but a distinct anomaly occurs over the diorite, which contains a high percentage of hornblende and magnetite. Over the altered volcanics and sheared diorite, the anomalies are large; there is one particularly sharp anomaly, which seems to indicate a magnetic body near the surface. This anomaly occurs just north of a straight line joining a mineralized shear zone 4½ miles southwest at Lumsden mine with a pyretized shear zone 3½ miles northeast on Peck creek. Whether it is actually associated with a major, partly-mineralized shear zone across Caledonia mountain, or whether it is only a local phenomenon can be ascertained only by more detailed work. Across the altered volcanics and sheared diorite, the anomalies apart from the unusually high one average about 700 gammas. But after the northern boundary of the volcanic rocks is passed, the intensity begins to decline gradually and reaches a minimum over the carboniferous rocks lying to the north of the mountain, as shown in Fig. 31. This change in the character of the curve at this northern boundary may possibly be a characteristic feature, which might help to distinguish elsewhere the concealed boundaries of pre-Carboniferous ridges.

CONCLUSIONS

It is apparent from the results of this investigation that anomalies up to 600 gammas may be expected over pre-Carboniferous ridges buried beneath a moderate amount of sedimentary cover. The south boundary of the Moncton ridge is definitely marked by high anomalies where it was crossed by the Calhoun and Main traverses (Fig. 28 and 29). The anomalies (Fig. 33) also give definite indication of the probable location of the south boundary of the ridge near Pine Glen, but, owing to lack of outcrops and wells in the vicinity, this cannot as yet be confirmed. However, high anomalies do not necessarily mark the boundaries of these ridges, as Fig. 32 shows at the south boundary of the Caledonia ridge.

The diorite and the type of granite containing a high proportion of biotite and hornblende are, with one exception, more magnetic than the other pre-Carboniferous rocks (Table 5). They would tend to produce the larger anomalies. The pre-Carbon-

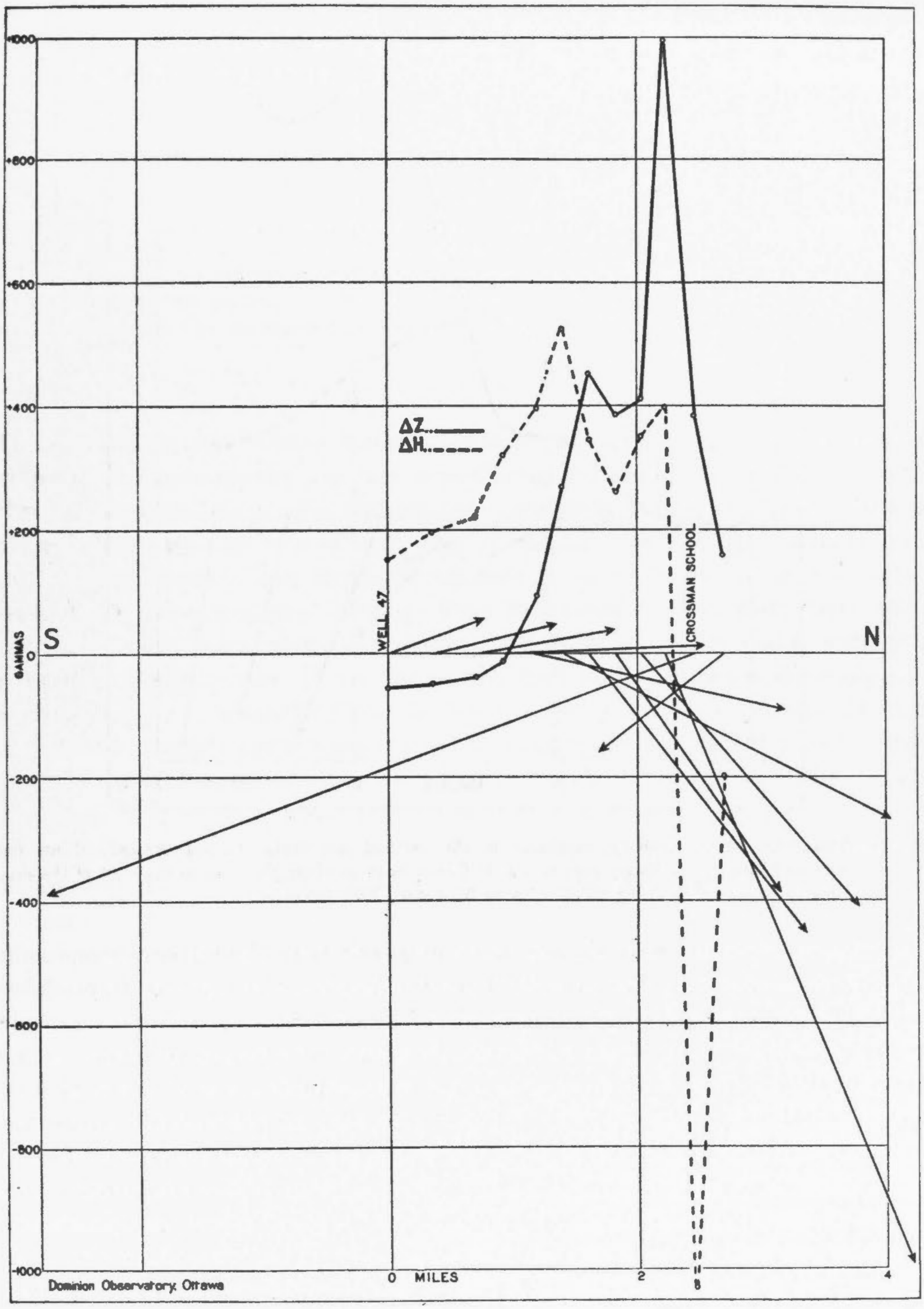

FIG. 33.—Magnetic profile showing anomalies in the vertical and horizontal intensities and anomaly vectors along Pine Glen traverse near Moncton, New Brunswick.

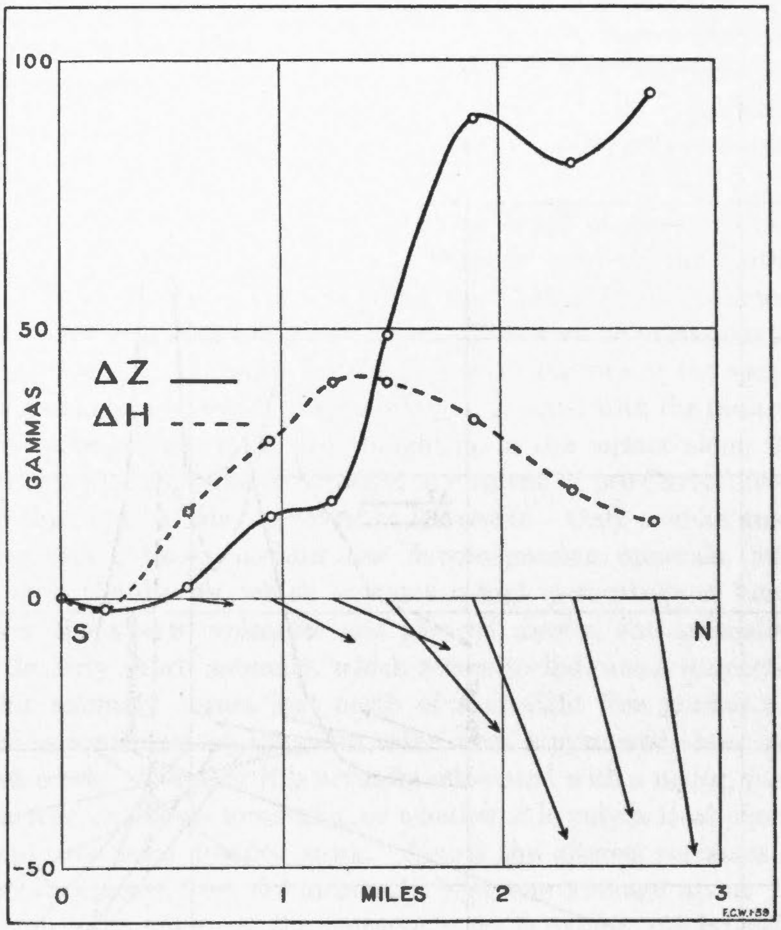

Fig. 34.—Magnetic profile showing anomalies in the vertical and horizontal intensities and anomaly vectors along the northerly part of Turtle Creek traverse along the road to the west of the creek from latitude 45° 58′·9 to 46° 01′·2 near Moncton, New Brunswick.

iferous volcanic rocks are only slightly more magnetic than the Carboniferous sedimentary rocks, but as they vary in magnetic character they may be expected to produce small anomalies. It is possible that the volcanic rocks contain local members considerably more magnetic than those tested. The chlorite schist, with included masses of ilmenite, obtained from well 92 is quite magnetic. Any considerable mass of this rock would be likely to produce a definite anomaly. The Carboniferous sedimentary rocks are only slightly magnetic, and appear to have little effect on the earth's normal field. The magnetic character of the diorite and the granite, high in ferromagnesian minerals, should be of great importance in outlining concealed ridges of pre-Carboniferous rocks by magnetic methods. Intrusions of diorite and granite occur irregularly here and there throughout the area of pre-Carboniferous rocks at Caledonia mountain. Similar scattered intrusions probably occur also in other concealed ridges of the pre-Carboniferous rocks. The presence of these intrusions, if sufficiently near the surface, would probably be indicated by definite anomalies, which should serve to outline areas underlain by pre-Carboniferous rocks, although it is well to remember that the volcanic rocks, if buried by a moderate cover, might produce only quite small anomalies.

APPENDIX III—TRAVERSES WITH TORSION BALANCE AND MAGNETOMETER OVER A BURIED "GRANITE" RIDGE NEAR MONCTON, NEW BRUNSWICK.

BY A. H. MILLER

ABSTRACT.—Three traverses with a torsion balance and a vertical magnetometer were made over this buried ridge in 1935. The same traverses had previously been covered with several types of magnetometer in 1932. In two of the traverses there was an apparent relation between the gravity anomaly and the form of the surface of the ridge. The maximum anomaly amounted to ·016 c.g.s.

The ridge was detected by the magnetometer on all three traverses.

INTRODUCTION

These traverses which were made in 1935 supplement work that was previously performed with magnetometers in this area during the season of 1932 (Appendix II). The three traverses of 1935 cover roughly the same ground as the Calhoun, Petitcodiac (main), and Pine Glen traverses of 1932 (Fig. 27 and 35). In 1935 the Calhoun traverse was shifted to the west of the Memramcook river so as to follow along the highways, and both it and the other two traverses were lengthened. Altogether about 40 miles were traversed: 11¼ miles along the Calhoun, 22 miles along the main, and 6½ miles along the Pine Glen traverse. Over the greater part of this distance the stations were usually from a fifth to a quarter of a mile apart. As there were in all only 131 torsion balance stations, the average station interval is approximately a third of a mile. Observations with a vertical magnetometer were made at each of the torsion balance stations.

As shown in the previous report, certain of the pre-Carboniferous rocks are highly magnetic, while others, like those of the later sedimentary formations (Mississippian and Pennsylvanian), are only weakly magnetic. Although there are, possibly, cases in which certain of the sedimentary rocks are of the same or even greater density than that of some of the pre-Carboniferous rocks, nevertheless, it seems to be the general rule for the sedimentary rocks to be lighter. From several measurements of density, by the writer, and over two hundred others, supplied by Dr. J. A. L. Henderson, it would appear that the average density of the sedimentary formations is not far from 2·5. These measurements also indicate a value of about 2·7 for the pre-Carboniferous. From the description of this latter formation by Dr. Norman, it may be judged that its average density is probably not very different from 2·67, the value usually taken for the average density of the outer crust of the earth. This would give an average density difference between the sedimentaries and the pre-Carboniferous of 0·17.

RESULTS

The torsion balance results for each station are tabulated in Tables 7, 8, and 9. The deduced relative values of gravity (Δg) are plotted in Fig. 36 and 37. As the directions of the main (Petitcodiac) and the Pine Glen traverses were usually within a few degrees of magnetic north, the components of the gradients and the differential curvatures for these two traverses are therefore approximately the components in the direction of

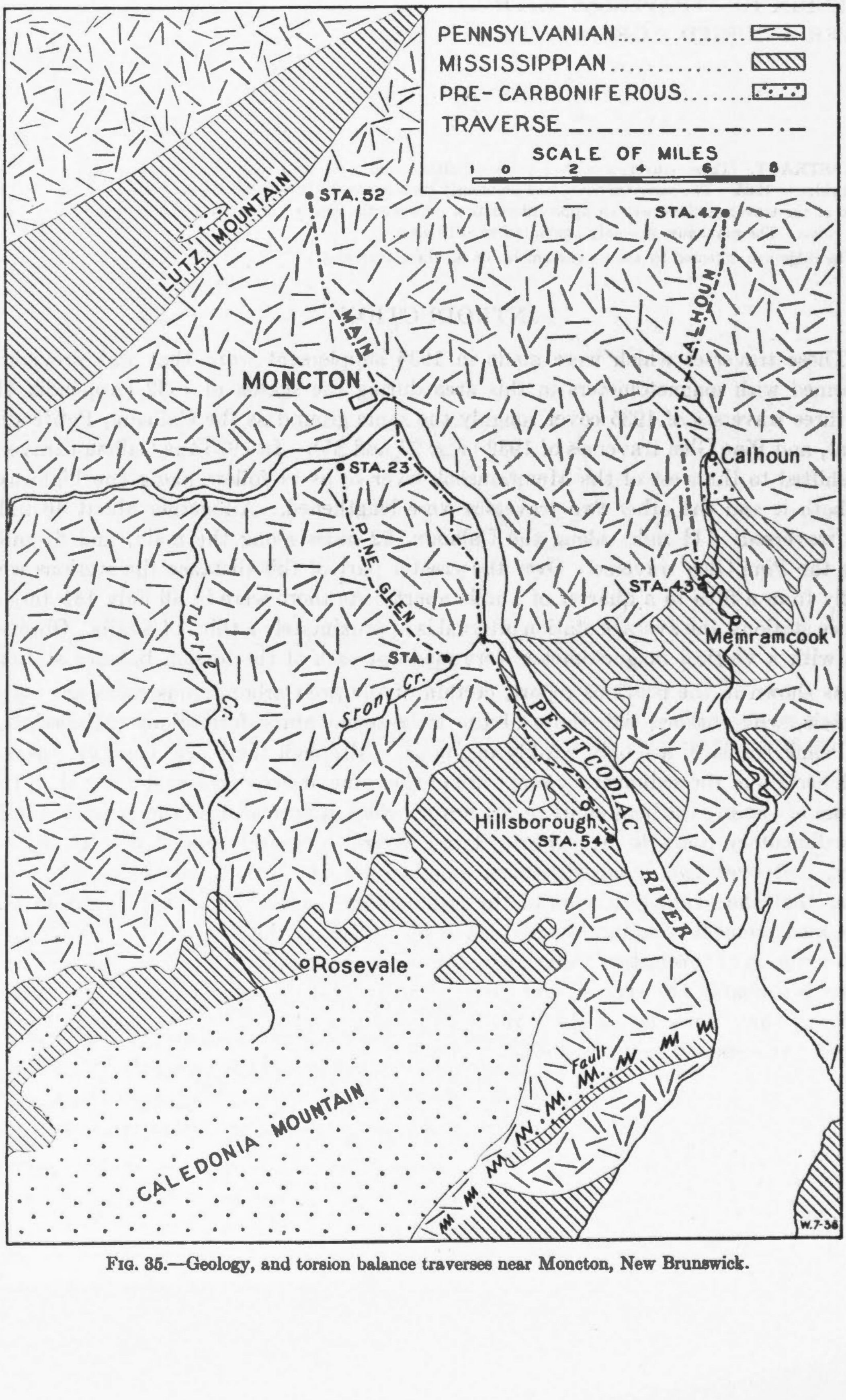

FIG. 35.—Geology, and torsion balance traverses near Moncton, New Brunswick.

magnetic north. For the initial azimuth, the torsion balance was set by compass in magnetic north. For conversion to astronomical bearings, the declination was assumed to be 24 degrees. This may be slightly in error over parts of the area covered by the traverses. Terrain corrections were obtained by levelling out to 60 metres from each station and by making use of the Moncton and Hillsborough topographical sheets (scale 1 inch to 1 mile, contour interval of 50 feet). The gradient terrains were often computed to 1 kilometre, but it was seldom that the effect was of importance beyond 60 metres. For the differential curvature, the terrain was evaluated wherever possible for a distance of 8 kilometres from the station. Soil density values of 1·7 and 1·8 were adopted for the area within the 60 metre circle, and 2·2 for that beyond. The computed gradient values are probably correct to within less than 5 E, but the curvatures for the southern parts of the Calhoun and main traverses, where the topography is rougher, may easily be from 5 E to 10 E in error, due to possible inaccuracies in the terrain correction.

The relative values of the vertical magnetic intensity (ΔZ) are plotted along with the gravity anomalies in Fig. 36 and 37. Other magnetic data are given in Appendix II. The three geological sections and the sketch map were prepared by Dr. G. W. H. Norman. The section for the main traverse is based on surface outcrops and wells between stations 53 and 26. South of station 53, the structure beneath the Hillsborough formation is assumed from the structure on the east side of Petitcodiac river.

Over the rougher ground the torsion balance results are complicated and their complete interpretation is difficult if not impossible. The most useful torsion balance result appears to have been the gravity anomaly, which at its maximum amounted to ·016 c.g.s., easily measurable with a pendulum apparatus or gravimeter.

Main traverse.—From station 54, south of Gray brook, to station 26, north of Mud creek (Fig. 36), it is apparent that the shape of the gravity anomaly curve conforms to that of the upper surface of the pre-Carboniferous, especially if allowance is made for reduction of scale for the ordinates of the gravity curve. It is possible, also, that from station 26 to the north end of the traverse at station 52 the gravity anomaly may give an indication of the otherwise unknown depth of the pre-Carboniferous. The difference in gravity between the maximum value at station 31, north of Mill creek, and the lowest value at station 57 is ·0157 c.g.s. For a density difference of ·17 this corresponds to a difference of elevation in the pre-Carboniferous of not less than 7,230 feet, corresponding in turn to approximately 9,500 feet, estimated by Dr. Norman, which is as good an agreement as could be expected, since both quantities are after all only estimates.

The major fault, shown at station 53, is indicated by the gradient to be somewhat farther south and in the vicinity of station 59. There is also a slight disturbance in the magnetic intensity at this latter station. Curvatures at these stations are difficult to interpret. There is, in fact, no very apparent curvature effect that can be attributed to the fault. Whatever this may be it is masked by a much larger curvature effect in a direction nearly at right angles to the section. The large curvature and the moderate gradient at station 52 are possibly the result of a combined effect of the fault and the rise in the pre-Carboniferous farther north.

A remarkable similarity exists between the gravity and magnetic curves from station 15 right through to the north end of the traverse, and it would seem likely that

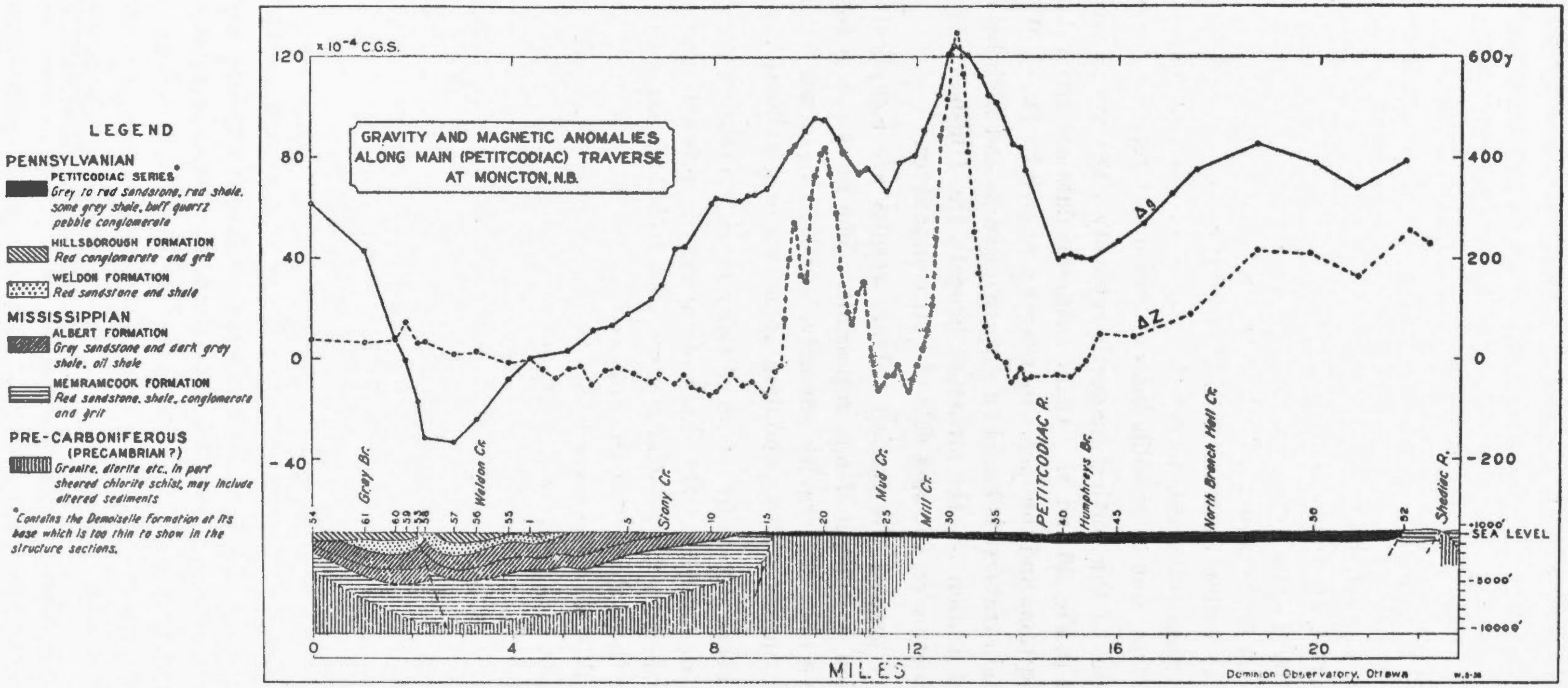

FIG. 36.—Gravity and magnetic anomalies along main (Petitcodiac) traverse—Moncton, New Brunswick.

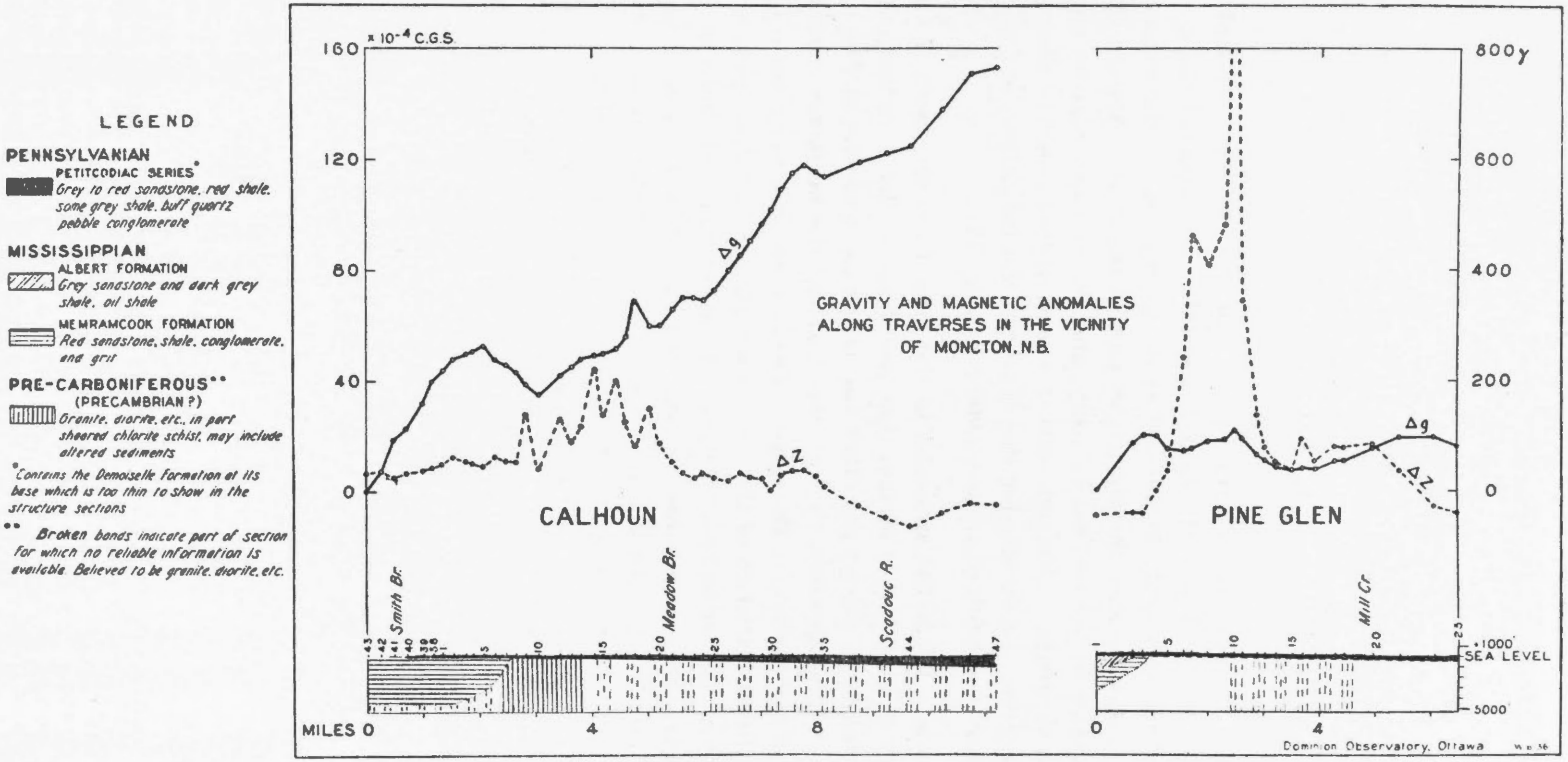

Fig. 37.—Gravity and magnetic anomalies along traverses in the vicinity of Moncton, New Brunswick.

these effects are due to the same cause—heavy magnetic rocks in the pre-Carboniferous formation.

Part if not all of the top of the ridge is indicated by the fluctuations in the vertical magnetic intensity (Fig. 36), and its southern edge is fairly well located by the sharp rise in the vertical intensity and by the maximum in the horizontal intensity (Fig. 29). An upper limit to the depth of the pre-Carboniferous is given by the intersections of the magnetic vectors at two places on this traverse. The depth of the intersection is, in each case, about 2,000 feet, whereas the depth to the pre-Carboniferous is estimated at only 500 feet.

Pine Glen traverse.—The rise in gravity (Fig. 37) is not so pronounced along this traverse, but here only the top of the ridge is crossed. The shape of the gravity curve probably again conforms roughly to the surface of the ridge along the section. As was the case with the main traverse, the uppermost part of the ridge is apparently indicated by the large anomalies in the vertical intensity, and the southern edge by characteristic variations in both elements. Although further measurements would be desirable for the purpose of constructing the vectors for this traverse, the indications are that an intersection would occur at a depth of around 2,000 feet (Fig. 33).

Calhoun traverse.—While the approach to the ridge from the south is indicated by the rise in gravity (Fig. 37), it is certain that the shape of the complete gravity curve does not correspond, as it did for the other two traverses, with the surface of the ridge along the section. It is apparent that on this traverse the magnetic intensity gives a better indication of the position of the ridge. The increase in gravity north of Meadowbrook is possibly due to variation of the density within the pre-Carboniferous formation. These changes, which appear to be abrupt, may be associated with faults or their gravitational equivalents. Such structures are indicated by the gradients and curvatures at three points north of Meadowbrook. The most northerly of these is at station 45 near Dorchester Crossing. From the gradient and curvature values and their variation, a rough estimate can be made of the depth of the supposed structures. Such an estimate for Dorchester Crossing indicates a depth probably somewhat less than 1,700 feet. The depth to the pre-Carboniferous at this point, estimated by Dr. Norman, is 1,000 feet.

The southern edge of the ridge is again accurately located by the sharp rise in the vertical intensity and by the maximum of the horizontal intensity (Fig. 28). Somewhat indefinite vector intersections occur at depths of about 1,000 feet. One is at a place where the ridge was exposed, and the other where the ridge is probably quite close to the surface.

TABLE 7—SUMMARY OF RESULTS—CALHOUN TRAVERSE

Station number	Miles from latitude 46° 00′ longitude 64° 36′·04		Astronomical bearing of traverse in degrees	Gradient of gravity			Differential curvature			Relative values of gravity in units of 10^{-4} c.g.s.
	North	East		Magnitude in Eötvös units	Astronomical bearing in degrees	Component in direction of traverse	Magnitude in Eötvös units	Astronomical bearing in degrees	Component in direction of traverse	
43	0·95	1·22	351·1	17·7	348·1	17·7	23·6	80·2	−23·6	0·00
42	1·20	1·11	351·3	25·1	30·4	19·5	22·6	62·2	−17·8	7·03
41	1·46	1·22	351·3	29·2	354·6	29·2	50·6	17·9	30·3	18·65
40	1·66	1·07	351·3	20·4	6·7	19·7	24·0	63·2	−19·4	22·85
39	1·97	1·18	351·3	23·9	325·9	21·6	16·9	80·1	−16·9	31·95
38	2·12	1·05	351·3	8·1	333·9	7·7	28·5	51·0	−14·0	39·51
1	2·29	1·00	351·3	20·7	352·9	20·7	21·4	35·5	0·6	43·49
2	2·48	1·00	351·3	9·6	35·4	6·9	20·2	55·9	−12·8	47·78
3	2·73	1·04	351·3	10·5	270·1	1·6	23·2	168·3	23·1	49·25
4	2·83	0·93	351·3	3·9	15·8	3·5	30·8	151·5	23·7	50·33
5	3·00	0·82	351·3	17·7	265·5	1·3	27·1	125·8	− 0·5	52·24
6	3·22	0·90	351·3	20·2	227·2	−11·3	23·5	33·0	2·7	47·31
7	3·43	0·89	351·3	9·2	271·2	1·6	7·9	70·0	− 7·3	45·35
8	3·60	0·84	351·3	21·5	179·8	−21·3	19·2	71·0	−18·0	42·80
9	3·77	0·81	351·3	24·7	232·2	−12·0	17·9	98·6	−14·7	38·05
10	4·00	0·84	351·3	12·4	276·5	3·3	35·3	1·2	33·2	34·67
11	4·38	0·69	351·3	24·3	288·2	11·0	7·1	118·8	− 1·8	41·74
12	4·59	0·70	351·3	11·1	341·7	10·9	47·0	53·5	−26·6	44·61
13	4·72	0·56	351·3	10·9	285·8	4·5	36·0	34·5	2·3	47·65
14	4·96	0·47	351·3	3·8	75·0	0·4	42·3	30·0	9·2	49·00
15	5·11	0·42	351·3	7·8	291·5	3·9	33·1	20·8	17·0	49·59
16	5·35	0·51	351·3	19·8	314·7	15·9	11·8	74·9	−11·5	51·40
17	5·50	0·40	351·3	15·3	271·9	2·8	15·2	38·7	− 1·3	55·80
18	5·66	0·33	351·3	13·0	292·9	6·8	28·0	22·8	12·7	58·07
19	5·92	0·34	351·3	13·5	272·9	2·7	26·2	75·4	−25·6	59·05
20	6·14	0·43	351·3	15·1	314·2	12·0	55·5	59·2	−39·8	59·19
21	6·40	0·41	17·7	19·7	39·2	18·3	9·6	60·0	0·9	64·66
22	6·56	0·48	17·7	12·6	26·1	12·5	52·9	18·2	52·9	69·02
23	6·76	0·58	17·7	16·5	241·5	−11·9	50·5	23·4	49·5	68·83
24	6·89	0·67	17·7	8·8	44·1	7·9	59·7	60·0	5·6	68·04
25	7·11	0·68	17·7	15·3	33·2	14·7	33·1	33·7	28·1	71·53
26	7·32	0·82	17·7	20·5	19·4	20·5	19·3	108·3	−19·3	78·79
27	7·51	0·89	17·7	14·8	39·4	13·8	14·5	87·5	−11·0	84·27
28	7·68	1·02	17·7	16·1	42·9	14·6	43·9	17·8	43·9	89·59
29	7·88	1·09	17·7	21·1	27·2	20·8	12·5	51·1	4·9	95·62
30	8·05	1·07	17·7	22·1	28·7	21·7	2·5	28·0	2·3	100·40
31	8·19	1·18	17·7	28·8	32·2	27·9	10·2	51·7	3·8	107·88
32	8·43	1·14	17·7	13·4	37·5	12·6	11·6	108·0	−11·6	113·88
33	8·62	1·20	17·7	8·0	58·8	6·0	6·1	23·8	6·0	116·47
34	8·82	1·28	17·7	15·4	191·8	−15·3	10·8	61·7	0·4	114·37
35	8·96	1·36	17·7	5·6	111·7	− 0·4	20·4	37·0	15·9	112·57
36	9·58	1·45	17·7	13·7	50·3	11·5	25·3	10·4	24·5	117·34
37	10·00	1·70	17·7	5·0	251·7	− 2·9	29·9	29·1	27·6	120·92
44	10·44	1·81	17·7	10·3	21·4	10·3	18·8	20·7	18·7	123·64
45	11·00	1·86	6·2	20·4	21·8	19·6	3·4	10·7	3·4	137·05
46	11·53	1·79	6·2	11·4	8·4	11·4	17·8	103·0	−17·3	149·51
47	12·00	1·98	6·2	5·0	221·0	− 4·1	16·7	105·1	−15·9	152·09

TABLE 8—SUMMARY OF RESULTS—MAIN (PETITCODIAC) TRAVERSE

Station number	Miles from latitude 45° 55′ longitude 64° 50′		Gradient of gravity			Differential curvature			Relative values of gravity in units of 10^{-4} c.g.s.
	North	East	Magnitude in Eötvös units	Astronomical bearing in degrees	Component in direction of magnetic north	Magnitude in Eötvös units	Astronomical bearing in degrees	Component in direction of magnetic north	
54	−0·51	9·74	23·2	211·4	−13·2	45·7	19·1	3·1	61·50
61	0·36	9·13	23·6	201·3	−16·6	95·5	13·3	25·5	42·41
60	0·99	9·10	50·5	203·2	−34·3	90·1	43·4	−63·4	8·17
59	1·11	8·84	68·5	179·9	−62·6	88·8	30·0	−27·3	− 0·83
53	1·28	8·61	52·5	164·0	−52·0	32·2	53·7	−29·3	−17·38
58	1·49	8·68	40·9	180·2	−37·3	24·0	56·3	− 22·6	−31·80
57	1·73	8·15	33·8	229·2	− 9·8	44·3	3·7	25·2	−33·18
56	1·87	7·74	9·7	252·5	1·1	115·6	19·5	6·2	−24·60
55	2·50	7·55	32·1	329·0	31·9	29·8	44·7	− 22·0	− 8·25
1	2·83	7·30	11·1	193·0	− 8·9	46·0	178·8	32·2	0·00
2	3·55	6·99	25·6	277·8	13·5	108·3	60·0	−106·0	2·88
3	3·97	6·72	16·4	251·6	1·6	71·6	32·1	− 27·0	11·13
4	4·35	6·67	11·0	326·0	10·8	10·9	54·7	− 10·1	13·23
5	4·66	6·59	11·8	293·4	8·7	4·3	46·4	− 3·3	17·63
6	5·04	6·36	19·7	259·5	4·6	107·8	17·1	14·7	23·75
7	5·25	6·28	28·8	314·2	26·7	68·4	41·7	− 45·2	28·99
8	5·47	6·07	42·0	272·0	18·4	24·4	144·8	22·5	43·54
9	5·70	6·14	42·3	308·7	37·6	50·8	148·7	49·2	44·19
10	6·23	6·03	25·1	273·5	11·6	39·4	25·8	− 6·6	61·39
11	6·32	5·97	23·8	269·8	9·6	20·0	160·6	19·7	63·91
12	6·77	5·99	27·8	268·0	10·4	47·6	42·4	− 32·3	62·69
13	6·93	5·96	21·4	291·2	15·2	51·8	48·0	− 41·9	64·69
14	7·06	5·97	28·7	272·0	12·6	42·4	41·6	− 27·9	64·96
15	7·32	5·93	11·3	292·4	8·2	38·9	50·9	− 33·6	67·37
16	7·76	5·71	31·5	355·6	29·7	39·5	41·1	− 25·5	82·26
17	7·82	5·68	14·7	8·0	12·5	23·0	27·7	− 5·3	84·81
18	7·96	5·50	25·8	332·2	25·7	35·7	34·2	− 15·9	90·32
19	8·14	5·46	10·5	18·7	7·7	34·5	31·5	− 12·4	95·35
20	8·31	5·38	24·0	85·9	− 8·2	18·5	46·2	− 14·3	95·05
21	8·55	5·27	29·6	133·6	−27·4	16·8	111·7	0·4	87·45
22	8·66	5·19	26·6	132·2	−24·3	15·0	136·3	11·6	81·61
23	8·97	5·23	25·4	227·9	− 7·9	9·2	50·2	− 7·8	73·44
24	9·14	5·06	22·5	245·5	− 0·2	22·0	150·8	21·6	75·31
25	9·51	5·19	38·3	270·2	15·7	60·7	100·4	− 22·0	66·27
26	9·60	4·93	15·5	262·1	4·3	43·1	6·4	21·1	77·51
27	9·85	4·75	16·6	253·3	2·1	6·4	133·8	4·6	80·67
28	9·91	4·55	46·6	264·5	14·8	55·6	78·2	− 50·7	90·27
29	10·23	4·44	88·2	278·4	47·2	34·4	155·2	34·4	104·49
30	10·37	4·30	45·8	273·0	20·8	23·7	13·3	6·3	120·94
31	10·42	4·22	11·0	213·6	− 5·9	28·9	6·2	14·3	124·00
32	10·56	4·01	25·9	167·1	−25·4	16·5	18·2	1·6	120·25
33	10·73	3·82	18·8	145·3	−18·5	36·1	161·5	35·4	111·97
34	10·81	3·69	21·4	153·0	−21·4	5·2	176·2	4·0	104·55
35	10·99	3·61	17·0	154·0	−17·0	11·5	115·5	1·8	101·53

TABLE 8—SUMMARY OF RESULTS—MAIN(PETITCODIAC) TRAVERSE—*Concluded*

Station number	Miles from latitude 45° 55′ longitude 64° 50′		Gradient of gravity			Differential curvature			Relative values of gravity in units of 10^{-4} c.g.s.
	North	East	Magnitude in Eötvös units	Astronomical bearing in degrees	Component in direction of magnetic north	Magnitude in Eötvös units	Astronomical bearing in degrees	Component in direction of magnetic north	
36	11·32	3·51	29·9	168·0	−29·2	26·0	31·5	− 9·3	84·97
37	11·44	3·48	24·7	162·5	−24·5	15·6	28·2	− 3·9	83·85
38	11·56	3·50	71·1	187·7	−60·5	27·2	33·4	− 11·8	74·69
39	12·23	3·60	5·7	348·1	5·6	9·1	36·3	− 4·6	39·38
40	12·32	3·49	9·3	346·6	9·1	22·7	10·3	8·3	40·90
41	12·44	3·41	11·0	78·0	− 2·3	19·1	150·0	18·7	41·37
42	12·49	3·32	12·0	50·0	3·3	25·4	60·7	− 25·0	40·42
43	12·58	3·24	10·9	66·0	0	9·8	48·3	− 8·0	40·14
44	12·64	3·04	15·6	358·6	14·4	30·2	11·1	10·2	39·44
45	13·00	2·59	5·0	320·8	4·8	13·0	31·6	− 4·7	46·30
46	13·52	2·47	13·1	327·2	12·9	30·1	151·2	29·7	53·43
47	14·01	2·24	15·5	348·7	15·1	21·5	1·4	13·6	65·63
48	14·46	2·02	12·5	18·1	9·3	5·2	53·5	− 4·7	75·37
49	15·53	1·46	4·5	48·0	1·4	33·4	77·6	− 30·7	84·92
50	16·65	1·24	15·9	117·1	−12·4	15·2	154·1	15·2	77·92
51	17·49	1·13	7·1	135·3	− 6·6	19·9	132·8	13·7	67·88
52	18·62	1·02	18·4	331·3	18·3	111·1	133·4	63·4	78·28

TABLE 9—SUMMARY OF RESULTS—PINE GLEN TRAVERSE

Station number	Miles from latitude 45° 55′ longitude 64° 50′		Gradient of gravity			Differential curvature			Relative values of gravity in units of 10^{-4} c.g.s.
	North	East	Magnitude in Eötvös units	Astronomical bearing in degrees	Component in direction of magnetic north	Magnitude in Eötvös units	Astronomical bearing in degrees	Component in direction of magnetic north	
1	4·81	5·00	40·7	333·5	40·7	21·7	23·1	− 1·6	0·00
2	5·18	4·48	10·3	53·0	2·3	43·6	9·0	17·8	16·96
3	5·44	4·44	9·8	0·7	8·9	25·0	43·3	−17·6	19·98
4	5·56	4·24	15·4	63·8	0·6	44·8	40·4	−28·1	19·45
5	5·62	4·01	7·3	90·1	− 3·0	28·2	51·2	−24·5	14·70
6	5·89	3·86	2·0	272·6	0·9	5·8	113·0	0·4	14·07
7	6·02	3·80	11·9	350·6	11·5	24·6	175·2	19·3	14·92
8	6·25	3·63	2·6	303·5	2·2	34·0	46·3	−26·3	17·86
9	6·56	3·59	10·9	86·9	− 3·9	39·6	44·5	−29·0	18·12
10	6·77	3·62	19·0	68·4	− 0·8	32·8	49·9	−27·7	21·47
11	6·91	3·52	16·7	130·8	−15·1	43·5	42·8	−30·0	18·62
12	7·07	3·30	7·2	92·6	− 3·2	9·3	90·5	− 6·1	12·77
13	7·16	3·16	8·3	150·5	− 8·3	23·8	63·5	−23·7	10·90
14	7·33	3·06	9·5	139·5	− 9·1	49·3	115·1	7·0	8·18
15	7·60	2·94	9·6	287·2	6·3	9·2	5·6	4·7	7·49
16	7·70	2·76	8·0	155·3	− 8·0	26·8	117·9	6·4	7·96
17	7·91	2·66	11·2	19·2	8·2	26·0	27·2	− 5·6	7·91
18	8·26	2·55	5·3	246·0	0	20·1	59·4	−19·6	10·42
19	8·37	2·42	3·1	236·8	− 0·5	17·3	33·7	− 7·4	10·85
20	8·80	2·10	12·9	284·7	8·1	74·5	98·4	−31·7	15·24
21	9·31	2·14	7·9	9·7	6·6	12·6	24·0	− 1·3	19·40
22	9·90	1·96	8·4	128·2	− 7·4	43·1	71·2	−42·4	19·50
23	10·33	1·86	8·5	97·1	− 4·4	24·9	80·5	−21·8	16·15

APPENDIX IV—TERRAIN CORRECTION

By A. H. Miller

ABSTRACT.—The method adopted for the evaluation of the terrain is a modification of the method of Schweydar. An example of the computation of the terrain effect is given for a torsion balance station. Terrain formulae coefficients are listed for radial distances of 0 to 1,000 metres for the gradient, and 0 to 10,000 metres for the curvature.

In evaluating the terrain correction, Schweydar's[1] method was used by the author. The torsion balance was set up with its centre of gravity one metre above the station, and elevations were taken in eight azimuths at radial distances suggested by Jung. These have seemed preferable to those originally given by Schweydar because they reduce the amount of levelling and computation and appear to be sufficiently closely spaced for the usual terrain. The coefficients, or multiplying factors (in Table 11, columns 5 and 10), corresponding to the new distances, were computed by the writer. Generally the computed values are in fair agreement with those given by Jung[2] and Haalck[3], but for certain values of ρ there are considerable discrepancies.

Usually, levels out to a distance of 60 metres from the station were taken with a five-inch Cooke transit, a metric rod, and a 50-metre tape on which were prominently marked the necessary radial distances in metres as required by the terrain formula. Use was made of field books prepared for recording the readings, and of special forms for facilitating the computation of the results. Although the gradient terrain at Moncton was computed for a distance of 1,000 metres, it was usually found in the other investigations that 60 metres was sufficient. In much of the work it was not unusual to carry the terrain corrections for curvature to a distance of one kilometre. In the work at Moncton this was extended to eight kilometres, a celluloid template being used to read the required elevations from the map, which was printed on a scale of one mile to the inch with a contour interval of 50 feet.

The accompanying tables illustrate the computation of the terrain at a torsion balance station at Malagash. Table 10 is a copy of the terrain field notes for the station, and Table 11 is a copy of the form on which the computation was made. The rod readings for the points at the various radial distances (ρ, column 1) are entered in columns 2, 4, 6, and 8 of the record book, as shown by Table 10. For example, referring to this table (column 2, rows 1, 2, and 3), 1·52 is the reading of the rod at the point 1·5 metres north of the station, *i.e.* in azimuth 1. The rod reading at 1·5 metres south of the station, *i.e.* in azimuth 5, was 1·46 metres. Under these two readings is their sum 2·98, which is entered on the computation form in its proper place, i.e. the first entry under S_{15} in the computation of U_{Δ}. To illustrate further, the rod reading 20 metres east (*i.e.* azimuth 3) was 1·87, and 1·14 at a distance of 20 metres west (azimuth 7) of the station. The rod reading at the torsion balance was 1·50 (shown opposite 'Rdg.' in the upper right corner of Table 10). To get the height of the centre of gravity

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[1] Zeitschrift für Geophysik III, 1927, pp. 17–23.

[2] Handbuch der Experimental Physik V, 3, 1930, pp. 174-5.

[3] Lehrbuch der Angewandten Geophysik, 1934, p. 66.

TABLE 10—TERRAIN FIELD NOTES FOR STATION 46 AT MALAGASH, NOVA SCOTIA

ρ	S_{15}	ΔH^2_{15}	S_{26}	ΔH^2_{26}	S_{37}	ΔH^2_{37}	S_{48}	ΔH^2_{48}	
	1·52	1·02	1·49	0·99	1·50	1·00	1·47	0·97	
1·5	1·46	0·96	1·45	0·95	1·47	0·97	1·48	0·98	Sta. 46
SΔ	2·98	+0·12	2·94	+0·08	2·97	+0·06	2·95	−0·02	Rdg. 1·50
	1·53	1·03	1·53	1·03	1·49	0·99	1·46	0·96	
3	1·42	0·92	1·41	0·91	1·37	0·87	1·43	0·93	h 1·00
SΔ	2·95	+0·21	2·94	+0·23	2·86	+0·22	2·89	+0·06	σ 1·6
	1·53	1·03	1·54	1·04	1·54	1·04	1·44	0·94	
5	1·39	0·89	1·29	0·79	1·40	0·90	1·46	0·96	
SΔ	2·92	+0·27	2·83	+0·46	2·94	+0·27	2·90	−0·04	−0·50
	1·58	1·08	1·66	1·16	1·63	1·13	1·44	0·94	
10	1·27	0·77	1·15	0·65	1·21	0·71	1·38	0·88	
SΔ	2·85	+0·57	2·81	+0·92	2·84	+0·77	2·82	+0·11	
	1·65	1·15	1·96	1·46	1·87	1·37	1·50	1·00	
20	1·12	0·62	0·98	0·48	1·14	0·64	1·43	0·93	
SΔ	2·77	+0·94	2·94	+1·90	3·01	+1·47	2·93	+0·14	
	1·82	−1·32	2·59	2·09	2·20	1·70	1·52	1·02	
40	0·77	0·27	0·60	0·10	1·20	0·70	1·55	1·05	
SΔ	2·59	+1·67	3·19	+4·36	3·40	+2·40	3·07	−0·06	
	2·05	1·55	2·74	2·24	2·44	1·94	1·43	0·93	
60	0·62	0·12	0·38	−0·12	0·79	0·29	2·12	1·62	
SΔ	2·67	+2·39	3·12	+5·00	3·23	+3·68	3·55	−1·76	

of the torsion balance above the terrain, it is only necessary to subtract ·50 from all the rod readings, as the torsion balance was itself set at 1 metre above the station. The heights of the centre of gravity of the torsion balance above the various terrain points are shown in columns 3, 5, 7, and 9 of Table 10. Beneath these entries, in the third row of each column, there are entered, for each value of ρ, the differences of the sums of the squares for the several corresponding points on opposite sides of the torsion balance. These are entered in their appropriate places on the computation form, as illustrated by Table 11.

Because rod readings instead of elevations have been used in computing the curvature in Table 11, the sign of the final values must be reversed. The terrain effects to 60 metres are thus, for U_Δ, $-2\cdot50$ E, and, for 2Uxy, $+1\cdot04$ E. Also, strictly speaking, in computing the gradient effects, differences in height between the terrain and the horizontal plane passing through the centre of gravity of the instruments are to be regarded as positive when the terrain is higher. In the case of the gradient, however, the sign of these differences is immaterial as we are concerned in the computation only with their squares.

The curvature coefficients for radial distances (ρ) of 1,500, 2,000, 3,000, 5,000, and 10,000 metres are ·03702, ·02670, ·02358, ·01835, and ·009042 respectively.

With the aid of a small computing machine, which was taken to the field, it was found that the computation could be made in this way with rapidity. The method has in its favour also the fact that, for the type of terrain that is as a rule encountered, it is fundamentally rigorous. Where we are concerned with squares, it is with the differ-

TABLE 11—TERRAIN COMPUTATION FOR STATION 46 AT MALAGASH, NOVA SCOTIA

ρ	ΔH^2_{26}	$-\Delta H^2_{48}$	Δ_{15} $\Delta_{26}-\Delta_{48}$		$-U_{xz}$	ΔH^2_{26}	$+\Delta H^2_{48}$	Δ_{37} $\Delta_{26}+\Delta_{48}$		$-U_{yz}$
1·5	+0·08	+0·02	+0·12 +0·10	×17·38 ×12·29	+2·09 +1·23	+0·08	−0·02	+0·06 +0·06	× 17·38 × 12·29	+1·04 +0·74
3	+0·23	−0·06	+0·21 +0·17	× 1·781 × 1·259	+0·37 +0·21	+0·23	+0·06	+0·22 +0·29	× 1·781 × 1·259	+0·39 +0·37
5	+0·46	+0·04	+0·27 +0·50	× 2·211 × 1·563	+0·60 +0·78	+0·46	−0·04	+0·27 +0·42	× 2·211 × 1·563	+0·60 +0·66
10	+0·92	−0·11	+0·57 +0·81	× 0·3754 × 0·2654	+0·21 +0·21	+0·92	+0·11	+0·77 +1·03	× 0·3754 × 0·2654	+0·29 +0·27
20	+1·90	−0·14	+0·94 +1·76	× 0·1903 × 0·1346	+0·18 +0·24	+1·90	+0·14	+1·47 +2·04	× 0·1903 × 0·1346	+0·28 +0·27
40	+4·36	+0·06	+1·67 +4·42	× 0·01569 × 0·01109	+0·03 +0·05	+4·36	−0·06	+2·40 +4·30	× 0·01569 × 0·01109	+0·04 +0·05
60	+5·00	+1·76	+2·39 +6·76	× 0·01312 × 0·009277	+0·03 +0·06	+5·00	−1·76	+3·68 +3·24	× 0·01312 × 0·009277	+0·05 +0·03
100	....	....	....	× 0·002586 × 0·001829	....	....	....	....	× 0·002586 × 0·001829	
150	....	....	....	× 0·001787 × 0·001264	....	....	....	....	× 0·001787 × 0·001264	
200	....	....	....	× 0·0003279 × 0·0002319	....	....	....	....	× 0·0003279 × 0·0002319	
300	....	....	....	× 0·0005253 × 0·0003714	....	....	....	....	× 0·0005253 × 0·0003714	
500	....	....	....	× 0·0001285 × 0·00009086	....	....	....	....	× 0·0001285 × 0·00009086	
1000	....	....	....	× 0·00007378 × 0·00005217	....	....	....	....	× 0·00007378 × 0·00005217	
Terrain Station 46................				$-U_{xz}$ $+U_{xz}$ $\times \sigma = 1·6$	+6·29 −6·29 −10·06	$H_n = z_n - h$ $h = 1$ metre			$-U_{yz}$ $+U_{yz}$ $\times \sigma = 1·6$	+5·08 −5·08 −8·13

TABLE 11—TERRAIN COMPUTATION FOR STATION 46 AT MALAGASH, NOVA SCOTIA

—Concluded

ρ	S_{15}	$-S_{37}$	$S_{15}-S_{37}$		$-U_\Delta$	S_{26}	$-S_{48}$	$S_{26}-S_{48}$		2Uxy
1·5	2·98	−2·97	+0·01	×34·85	+0·35	2·94	−2·95	−0·01	×34·85	−0·35
3	2·95	−2·86	+0·09	×23·29	+2·10	2·94	−2·89	+0·05	×23·29	+1·16
5	2·92	−2·94	−0·02	×16·58	−0·33	2·83	−2·90	−0·07	×16·58	−1·16
10	2·85	−2·84	+0·01	×10·56	+0·11	2·81	−2·82	−0·01	×10·56	−0·11
20	2·77	−3·01	−0·24	× 5·404	−1·30	2·94	−2·93	+0·01	× 5·404	+0·05
40	2·59	−3·40	−0·81	× 2·256	−1·83	3·19	−3·07	+0·12	× 2·256	+0·27
60	2·67	−3·23	−0·56	× 1·178	−0·66	3·12	−3·55	−0·43	× 1·178	−0·51
100				× 0·7323					× 0·7323	
150				× 0·3702					× 0·3702	
200				× 0·2670					× 0·2670	
300				× 0·2358					× 0·2358	
500				× 0·1835					× 0·1835	
1000				×0·09042					× 0·09042	
				$-U_\Delta$	−1·56				+2Uxy	−0·65
Locality, Malagash..............				$+U_\Delta$	+1·56					
				$\times\sigma = 1·6$	+2·50				$\times\sigma = 1·6$	−1·04

ences of the squares of two quantities in the final computation (Table 11). These differences are most rapidly formed by multiplying, in each case, the sum of the two quantities by their difference. Many of them may be written down by inspection, particularly those for the inner circles.

APPENDIX V—ON THE RELATION BETWEEN MAGNETIC AND GRAVITY ANOMALIES

BY A. H. MILLER

ABSTRACT.—The equations of Eötvös expressing the relation between second derivatives of the gravitational potential and the magnetic force are given along with their application by the author to the determination of the magnetic field of certain ideal structures, including the uniformly magnetized sphere. Some observations of a general nature are made regarding the magnetization of geological structures.

Certain relations, as originally shown by Eötvös[1], exist between the magnetic force (the magnetic anomaly) produced by a body and the corresponding second derivatives of its gravitational potential. While these may not be of great practical importance, they are at least of very considerable theoretical interest.

The following groups of equations (1), (2), and (3) were given by Eötvös, and the remarks accompanying them in quotation marks are a rather free translation of the original German.

"The magnetic force exerted by a body is not proportional to its force of attraction but to the gradient of this attractive force.

If X, Y, Z represent the components of the magnetic force, which a body (mass) exerts, for which the components of magnetization α, β, γ are constant, and further if V represents the potential of the attracting mass, G the gravitation constant, and σ the density, the equations then are:—

$$\left.\begin{aligned} X &= \frac{\alpha}{G\sigma}\frac{\partial^2 V}{\partial x^2} + \frac{\beta}{G\sigma}\frac{\partial^2 V}{\partial x \partial y} + \frac{\gamma}{G\sigma}\frac{\partial^2 V}{\partial x \partial z}, \\ Y &= \frac{\alpha}{G\sigma}\frac{\partial^2 V}{\partial x \partial y} + \frac{\beta}{G\sigma}\frac{\partial^2 V}{\partial y^2} + \frac{\gamma}{G\sigma}\frac{\partial^2 V}{\partial y\, dz}, \\ Z &= \frac{\alpha}{G\sigma}\frac{\partial^2 V}{\partial x \partial z} + \frac{\beta}{G\sigma}\frac{\partial^2 V}{\partial y \partial z} + \frac{\gamma}{G\sigma}\frac{\partial^2 V}{\partial z^2}. \end{aligned}\right\} \cdots\cdots\cdots\cdots\cdots\cdots (1)^2$$

In case the magnetization is not homogeneous these equations hold for only an infinitely small volume element of the mass, and if this (mass) is enclosed in another, then the quantities α, β, γ and also σ are to be replaced by the differences corresponding to the two separate masses. Applying the relation $\Delta V = O^*$, we then obtain:—

$$\left.\begin{aligned} X\beta - Y\alpha &= \frac{\alpha\beta}{G\sigma}\left(\frac{\partial^2 V}{\partial x^2} - \frac{\partial^2 V}{\partial y^2}\right) + \left(\frac{\beta^2-\alpha^2}{G\sigma}\right)\frac{\partial^2 V}{\partial x \partial y} + \frac{\beta\gamma}{G\sigma}\frac{\partial^2 V}{\partial x \partial z} - \frac{\alpha\gamma}{G\sigma}\frac{\partial^2 V}{\partial y \partial z}, \\ 2\gamma X + \alpha Z &= \frac{\alpha\gamma}{G\sigma}\left(\frac{\partial^2 V}{\partial x^2} - \frac{\partial^2 V}{\partial y^2}\right) + \frac{2\beta\gamma}{G\sigma}\frac{\partial^2 V}{\partial x \partial y} + \frac{(2\gamma^2+\alpha^2)}{G\sigma}\frac{\partial^2 V}{\partial x \partial z} + \frac{\alpha\beta}{G\sigma}\frac{\partial^2 V}{\partial y \partial z}, \\ 2\gamma Y + \beta Z &= -\frac{\beta\gamma}{G\sigma}\left(\frac{\partial^2 V}{\partial x^2} - \frac{\partial^2 V}{\partial y^2}\right) + \frac{2\gamma\alpha}{G\sigma}\frac{\partial^2 V}{\partial x \partial y} + \frac{\alpha\beta}{G\sigma}\frac{\partial^2 V}{\partial x \partial z} + \frac{(2\gamma^2+\beta^2)}{G\sigma}\frac{\partial^2 V}{\partial y \partial z}, \end{aligned}\right\} \quad (2)$$

by means of which there is expressed the connection between the magnetic effects and those quantities which can be ascertained with the torsion balance.

In case the magnetic masses are uniformly distributed along a line (for example, in the direction of y), these equations can be much simplified:—

$$\left.\begin{aligned} X &= \frac{\alpha}{G\sigma}\frac{\partial^2 V}{\partial x^2} + \frac{\gamma}{G\sigma}\frac{\partial^2 V}{\partial x \partial z}, \\ Y &= 0, \\ Z &= -\frac{\gamma}{G\sigma}\frac{\partial^2 V}{\partial x^2} + \frac{\alpha}{G\sigma}\frac{\partial^2 V}{\partial x \partial z}, \end{aligned}\right\} \cdots\cdots\cdots\cdots\cdots\cdots (3)$$

where it is to be remarked that, since $\frac{\partial^2 V}{\partial y^2} = 0$, $\frac{\partial^2 V}{\partial x^2}$ is directly determinable with the torsion balance.

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[1] Bestimmung der Gradienten der Schwerkraft und Ihrer Niveauflächen mit Hülfe der Drehwage—1er Band der Abhandlungen der XV Allgemeinen Konferenz der Erdmessung in Budapest 1906, pp. 56–59.

[2] This set of equations is easily derived from the consideration of the field of a magnetic molecule or dipole. Cf. Theoretische Physik, third edition, 1910, by Christiansen and Müller, pp. 302–5, or translation of earlier edition by W. F. Magie, 1897, pp. 166-7.

[*] $\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = 0$ (outside the body).

These relations prove convincingly that the larger magnetic anomalies are not to be sought where the pendulum reveals marked anomalies in the normal acceleration. In the case of a flat shaped magnetic body the anomalies are largest not in the centre but on the boundaries, consequently along the tectonic lines, as Ed. Naumann has proven by an appropriate compilation of many observations."

By substituting in equations (3) and determining the components of magnetization from the equations $\alpha = \kappa A$, $\beta = \kappa B$, $\gamma = \kappa C$, where κ is the magnetic susceptibility, and A, B, and C are the components of the earth's field, Eötvös goes on to show that, for certain eruptive rocks in places where the gradient is only one Eötvös unit, the magnetic anomaly due to induced magnetism may amount to as much as 10 gammas. This may be increased by the effects of remanent magnetism.

The writer is not aware that any serious attempts have been made in the field to compare measured magnetic anomalies with the gravitational potential derivatives, as suggested by the Eötvös equations. But, because of the fact that the second derivatives of the potential have now been worked out for a considerable number of structures of various forms, these equations afford a convenient means of determining the magnetic effect of such assumed masses on the assumption of uniform magnetization.

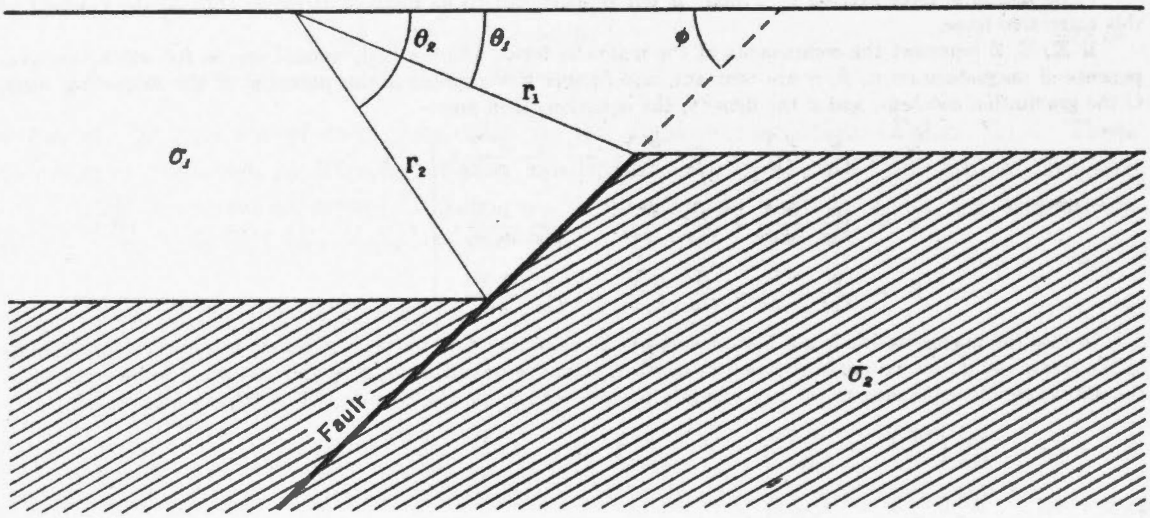

FIG. 38.—Illustrating an inclined fault.

For the structure, represented by Fig. 38, assumed infinite in the direction of y,

$$-\frac{\partial^2 V}{\partial x^2} = 2G\sigma \sin\Phi \left[\cos\Phi \log_e \frac{r_2}{r_1} - \sin\Phi\,(\theta_2 - \theta_1)\right],$$

$$\frac{\partial^2 V}{\partial x\,\partial z} = 2G\sigma \sin\Phi \left[\cos\Phi\,(\theta_2 - \theta_1) + \sin\Phi \log_e \frac{r_2}{r_1}\right],$$

from which it follows, applying equations (3),

$$X = 2\,(\theta_2 - \theta_1) \sin\Phi\,(\alpha \sin\Phi + \gamma \cos\Phi) + 2 \log_e \frac{r_2}{r_1} \sin\Phi\,(\gamma \sin\Phi - \alpha \cos\Phi),$$

$$= 2 \sin\Phi \left[M_n\,(\theta_2 - \theta_1) + M_s \log_e \frac{r_2}{r_1}\right],$$

$$Z = 2\,(\theta_2 - \theta_1) \sin\Phi\,(\alpha \cos\Phi - \gamma \sin\Phi) + 2 \log_e \frac{r_2}{r_1} \sin\Phi\,(\alpha \sin\Phi + \gamma \cos\Phi),$$

$$= 2 \sin\Phi \left[M_n \log_e \frac{r_2}{r_1} - M_s\,(\theta_2 - \theta_1)\right],$$

where $M_n = \alpha \sin \Phi + \gamma \cos \Phi$ is the component of magnetization perpendicular to the fault plane, and $M_s = \gamma \sin \Phi - \alpha \cos \Phi$ is the component parallel to this surface.

The same expressions for the second derivatives of the gravitational potential, and for the components of the magnetic force, also apply to the dyke, if (Fig. 26) θ is designated by Φ, and α is designated by θ.

Perhaps the most interesting application of the Eötvös equations is to the determination of the external field of a uniformly magnetized sphere. The equivalence of the sphere and the small magnet is at once apparent because the gravitational derivatives are the same for a finite sphere as for the same mass concentrated at a point which might be regarded as a magnetized molecule.

For the sphere: $\dfrac{\partial^2 V}{\partial x^2} = G\mu \dfrac{3x^2 - r^2}{r^5}$, with similar expressions for $\dfrac{\partial^2 V}{\partial y^2}$, and $\dfrac{\partial^2 V}{\partial z^2}$; $\dfrac{\partial^2 V}{\partial x \partial y} = 3\,G\mu \dfrac{xy}{r^5}$, $\dfrac{\partial^2 V}{\partial x \partial z} = 3\,G\mu \dfrac{xz}{r^5}$, and $\dfrac{\partial^2 V}{\partial y \partial z} = 3\,G\mu \dfrac{yz}{r^5}$, where $\mu = v\sigma$, where v is the volume of the sphere and μ its mass. By substitution in equation (1) there is obtained:—

$$X = \frac{v}{r^5}\left[\alpha(3x^2 - r^2) + 3\,\beta xy + 3\gamma xz\right],$$

$$Y = \frac{v}{r^5}\left[3\alpha xy + \beta(3y^2 - r^2) + 3\gamma yz\right],$$

$$Z = \frac{v}{r^5}\left[3\alpha xz + 3\,\beta yz + \gamma(3z^2 - r^2)\right].$$

If the direction of magnetization coincides with the x axis,

$$\left.\begin{aligned} \beta = \gamma = 0, \quad X &= \frac{v\alpha}{r^5}(3x^2 - r^2) = \frac{M}{r^5}(3x^2 - r^2), \\ Y &= \frac{3v\alpha}{r^5}\,xy = \frac{3M}{r^5}\,xy, \\ Z &= \frac{3v\alpha}{r^5}\,xz = \frac{3M}{r^5}\,xz, \end{aligned}\right\} \quad \cdots\cdots \quad (4^*)$$

where M is the magnetic moment of the sphere.

Applying these to the well known case of a small magnet in the first position of Gauss, for which $x = r$, $y = 0$, and $z = 0$, if follows that $Y = Z = 0$, and $X = \dfrac{2M}{r^3}$, and for the second position, for which $x = 0$, and $z = r$, $Y = Z = 0$, and $X = -\dfrac{M}{r^3}$, the sign indicating that

---

* Since $\dfrac{\partial^2 V}{\partial^2 x^2} = -\dfrac{4}{3}\pi G\sigma$, inside the sphere, the internal field equals $-\dfrac{4}{3}\pi\alpha$, from (1). (Surface density equals $\alpha \cos \lambda$).

for this position the field is in a direction opposite to the magnetization. The resultant field at any point xyz is

$$R = (X^2 + Y^2 + Z^2)^{\frac{1}{2}}$$

$$= \frac{M}{r^3}\left(1 + \frac{3x^2}{r^2}\right)^{\frac{1}{2}} \text{. . . . . from (4)}$$

$$= \frac{M}{r^3}(1 + 3\cos^2\lambda)^{\frac{1}{2}},$$ where λ is the angle that the direction of $r = (x^2+y^2+z^2)^{\frac{1}{2}}$ makes with the direction of x, the direction of magnetization. It may also be shown, from the expression for the corresponding direction cosines, that the angle ϵ, between the resultant force and r, bears to λ the relation $2 \tan \epsilon = \tan \lambda$.

In the field work of the writer, it was found that, in a limited number of cases (for example, the Pennington dyke), the main features of the magnetic field of the structure were in good general agreement with what was to be expected from uniform magnetization induced by the earth's field. Such apparent uniformity is however by no means the rule, nor is it to be expected, because rock of apparently the same formation may vary greatly in magnetic susceptibility from one point to another.

It may be accepted, with almost absolute certainty, that there is no such thing as uniform magnetization in either ore bodies or rock formations, although it may be approached in certain cases. To represent completely the field of a magnetized body, there is usually required not only a distribution of magnetic charge over the surface of the body (as in the case of uniform magnetization) but also a distribution throughout its volume as well. The volume distribution, which may be expected to be accompanied by surface distributions within the structure itself, will be more complicated the more variable the susceptibility within the body. Consequently it is bound to be very difficult or impossible to predict what the magnetic field of a geological structure may be, and conversely equally difficult to say what the structure may be from observation of its magnetic effect.

Over large areas of the main serpentine intrusive in the vicinity of Thetford, Quebec, the magnetic field is extremely complicated, but it does appear to the writer to arise largely from induction by the earth's field. The average vertical intensity appears to be above normal. A number of intense magnetic poles, lying apparently at a depth of approximately fifteen feet and producing anomalies in the vertical intensity up to 15,000 gammas or over, were located in observations over the area. Four out of the five encountered were south poles producing positive anomalies. As no definite indication was observed of the corresponding north poles, it was supposed that they were located at some greater depth. The only exceptionally strong north pole that was located appeared to form part of a magnet lying approximately horizontally in the rock, with its corresponding south pole at a distance of from 50 to 60 feet, in a direction within a degree or so of magnetic south (Fig. 5). In the Moncton traverses, it will be noticed again that the anomalies of any account are positive.

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