CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
DOMINION OBSERVATORIES

PUBLICATIONS

OF THE

Dominion Observatory

OTTAWA

Volume XVI

EDMOND CLOUTIER, C.M.G., O.A., D.S.P.
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
OTTAWA 1955

TABLE OF CONTENTS

CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
DOMINION OBSERVATORIES

PUBLICATIONS

OF THE

Dominion Observatory

OTTAWA

Vol. XVI, No. 1

Interpretations of Gravimetric and Magnetic Anomalies on Traverses in the Canadian Shield in Northern Ontario

BY

G. D. GARLAND

OTTAWA
EDMOND CLOUTIER, C.M.G., O.A., D.S.P.
PRINTER TO THE KING'S MOST EXCELLENT MAJESTY
CONTROLLER OF STATIONERY
1950

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS—*Concluded*

TABLES

Showing names, locations and Bouguer anomalies for gravity stations

Interpretations of Gravimetric and Magnetic Anomalies on Traverses in the Canadian Shield in Northern Ontario

BY

G. D. GARLAND

ABSTRACT

The Bouguer anomalies obtained on gravity traverses over the Canadian Shield in northern Ontario are separated into local and regional effects. The latter are evidently too extensive to be directly attributed to surface formations, and apparently result from conditions deep within the crust. Two characteristic strike directions are exhibited by these regional trends, east-west and northeast-southwest, allowing them to be separated into two age groups. The first (east-west striking) group of structures apparently dates from early Precambrian times, as it closely parallels folding and thrust faulting in the Timiskaming sediments, while the second (northeast-southwest striking) group is believed to result from tectonic activity of Huronian age.

Interpretation of these anomalies has been based on the assumption of a layered crust, consisting of an upper, or granitic layer, underlain by a basaltic layer. It is shown that the majority of the regional anomalies cannot be explained by structures at a depth as great as the base of the basaltic layer (36 kilometers), but could be caused by irregularities in the thickness of the granitic layer. For example, a marked gravity low, indicating a thickened granitic layer, trends east-west just south of the Kirkland Lake thrust zone. It would appear that this represents the remnant of the root of an early Precambrian mountain range, as the surface rocks along the low are dominantly granite, while Precambrian sediments and volcanics are preserved north and south of the low. A second root structure is suggested along the northwest limit of the Grenville province, where a line of thrust mountains is believed to have formed during Huronian time.

In contrast to these areas of low gravity, regions of relatively high anomaly are found to be largely covered by Precambrian sediments. The implication is that these regions were low basins in Precambrian times, so that the surface rocks were preserved from the great erosion which bared such large masses of granite elsewhere.

The conclusion is, therefore, that irregularities in the granitic layer exist as a result of Precambrian mountain-building processes, and that these irregularities produce the broad, regional gravity anomalies. A departure from isostatic equilibrium is thus indicated, since the root structures have long outlived the topographic features they once supported.

The more local gravity anomalies of the Shield are found to have a direct correlation with the known surface geology. That is, small, well defined highs are observed over belts of relatively dense Keewatin lavas, with the geological contacts quite accurately demarcated by the inflection points of the gravity profiles. By comparison of the observed curves with those calculated for type bodies, an estimate may be made of the depth to the base of the Keewatin rocks. Such estimates are of interest because of the ore deposits found within the lavas. For some of the broader lava belts, depths up to ten thousand feet are indicated.

INTRODUCTION

In the study of the history and structure of the Canadian Shield, geophysical methods, such as seismology, gravity, magnetism, and radio-activity, are coming more and more into use. The present paper is an analysis of the results of several gravimeter surveys made over the Shield area of northern Ontario and northwestern Quebec during the past few years, in an attempt to correlate the gravity anomalies with major structural trends. By combining the gravity results with recent information on the crustal layers of the region (as determined seismologically) and with tectonic studies, it is believed that a much more complete picture of this very important and interesting area is possible.

While the emphasis has been on interpreting the regional gravity variations, the use of the gravimeter in the more detailed study of Precambrian surface geology has not been forgotten. Toward the end of the paper, there are some examples which indicate what information is to be obtained from traverses over comparatively local structures.

GRAVITY MEASUREMENTS IN NORTHERN ONTARIO AND QUEBEC

The area under study extends from Ottawa to the Manitoba Boundary, and north to Moosonee. However, much of this is covered only by a few reconnaissance surveys. Detailed coverage is largely limited to the North Bay-Rouyn-Timmins triangle. Measurements of gravity in the area date from the establishment several years ago of pendulum stations by the Dominion Observatory at such points as Mattawa, Sudbury, New Liskeard and Cochrane. The earliest gravimeter traverse was that from Ottawa through North Bay and Sudbury to Sault Ste. Marie, using a Humble Oil Company instrument. During the summers of 1946 and 1947, most of the remaining stations were established with an Atlas Exploration Company gravimeter. The traverse from Cochrane to Moosonee was observed in 1947, with a North American Geophysical Company instrument.

None of the traverses can be said to be "looped" in the usual sense of the word. However, many stations along the main traverses have been repeated, so that any large drift error is guarded against. Most of the shorter traverses have been tied to one or more of these repeated bases. In the future, better ties will undoubtedly be made, and many of the present values of observed gravity may have to be adjusted. However, it is very unlikely that the magnitude of such adjustments will be sufficient to affect the interpretations which follow.

Observational routine on regional surveys of this kind is necessarily different from the methods of commercial surveys, where the work is carried on in a comparatively small area. For a regional traverse, a station spacing of four to six miles is usually satisfactory, as the structures sought are several miles broad. Stations are chosen at points which are readily identifiable on topographic map sheets, and preferably at points of known elevation. If intermediate stations are required, the elevations are obtained by aneroid barometer readings, which are usually accurate within five feet. In the case of a detailed prospecting survey, the stations may be only a few hundred feet apart. Base stations may thus be repeated every few hours, allowing the instrumental drift factor to be largely eliminated. Since very small anomalies are important in such work, the station elevations are obtained to within a fraction of a foot, by running levels during the survey.

COMPUTATION OF ANOMALIES

A gravity anomaly is the difference between the observed value of the acceleration of gravity (g) and some calculated value for the same station. Various types of anomaly are thus possible, depending on the assumptions adopted in obtaining the calculated value. Throughout the discussion, use is made entirely of the Bouguer anomaly, which allows for the decrease in gravity with altitude and also for the attraction of a layer of rock of thickness equal to the elevation of the station and extending laterally theoretically to infinity, but makes no correction for isostatic compensation.

The actual method of calculation is as follows:

First, the latitude of the station is scaled from a topographic map. (In most cases, the 8-mile sheets were used, the latitude being read to 0·1 minute. The error possible is several tenths of a minute in uncertain cases). Normal gravity at sea level is assumed to vary with latitude according to the International Formula, which is:

$$\gamma_0 = 978.049\,(1+0.0052884\,\sin^2\Phi - 0.0000059\,\sin^2 2\Phi)\ \text{cm/sec}^2,$$

where Φ is the latitude. Thus, having found Φ as above, γ_0 may be determined. To this theoretical gravity are applied the correct factors for the height of the station above sea level, and for the attraction of the plateau between the station and sea level. Material in this infinite sheet is assumed to have a uniform density of 2·67 grams per cubic centimetre. There is thus obtained a value of computed gravity for the given station, calculated according to the stated assumptions. The difference between this value and the observed gravity gives the Bouguer anomaly.

Just as there were differences noted between the field procedures of regional and detailed gravity surveys, so do the calculation methods differ also. When small anomalies are important, corrections must be made for topography in the vicinity of the stations. This correction is usually omitted in regional surveys, partly because of a lack of contour maps in most areas, also because the correction is negligible in considering large anomalies. Also, in making the Bouguer correction, the practice in commercial surveys is to estimate as closely as possible the actual density of rock material between the station and the datum plane, rather than assuming the average value of 2·67 grams per cubic centimetre. The aim in detailed gravimetric surveys is to obtain anomalies accurate to 0·1 milligal, since an anomaly of a few tenths of a milligal may be commercially important. The anomalies quoted below are believed correct to 1 or 2 milligals, which is sufficiently close for the study of structures whose effect is measured in tens of milligals.

The choice of Bouguer, rather than isostatic, anomalies for the study of major structures may be mentioned here. It is the purpose of the present analysis to suggest structures at certain depths within the crust, as determined seismologically, which will satisfy the gravity observations, and for this purpose the Bouguer anomalies are the proper ones to use. The relationship between these structures and isostatic compensation is suggested, but it is not the purpose here to test the classical methods of isostatic reduction.

MAGNETIC MEASUREMENTS IN NORTHERN ONTARIO AND QUEBEC

In recent years, many magnetic surveys have been made in rather limited areas in the mining districts of northern Ontario and Quebec. However, little if any use has been made, to date, of these magnetic observations in studying the major structures of the Shield. During the summer of 1947, readings were taken at gravity stations along certain of the traverses across the Shield, in an attempt to find a correlation between the larger gravity and magnetic anomalies.

Magnetic observations on such a regional scale involve difficulties not met in more local surveys. The repetition of base stations, in order to correct diurnal variations, was usually not possible. Instead, the time of each observation was carefully noted, and a correction was later obtained by measuring the records of Agincourt Magnetic Observatory at these times, thus reducing all stations to a uniform datum. In spite of this, some stations may be in error by 25 gammas (possibly more) from diurnal variations alone. More serious is the effect of magnetic material in the vicinity of the stations. All locations, of course, were chosen remote from artificial influences, and as much as possible from obviously magnetic rock material. It is believed, however, that many of the stations suffer from local effects several times greater than the regional trends sought. In this respect, the airborne magnetometer would appear useful in studying large structures, as purely local effects are minimized by it. Also, the continuous profiles obtained should clearly show any gradual trends which might not be evident from a ground survey.

INTERPRETATION OF GRAVITY ANOMALIES

After the Bouguer anomalies have been computed, they are plotted in the form of profiles for each traverse. An attempt must then be made to interpret each profile, that is, to suggest a geological structure which could produce the desired effect. It is characteristic of gravity, and incidentally other force field anomalies, that no unique interpretation is possible, due to the number of unknowns and also to the uncertainty of the observed profile. Some of the unknowns that may be mentioned are the depth and form of anomalous structure, and the density contrast between the structure and surrounding rock.

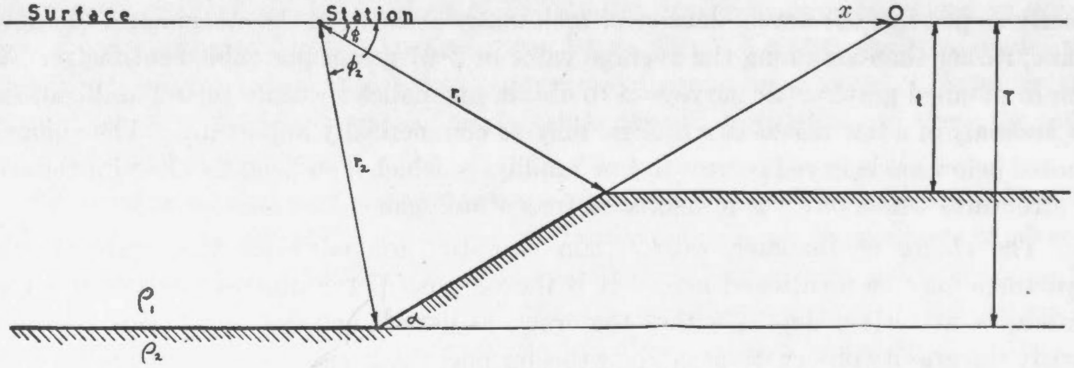


FIG. 1. Explanation of symbols used in the formula for the attraction of a step.

In order to lessen these unknown factors, certain assumptions have been made regarding the regional structures. First, the seismologists' picture of a layered crust is adopted, in which the crust proper consists of an upper or granitic layer, and an "intermediate" or basaltic layer. (The term "Intermediate" is not intended to indicate its petrographical nature). Beneath these two layers is the mantle of ultrabasic rock, extending inwards toward the core of the earth. Thicknesses of the granitic and intermediate layers have been determined in various parts of the world. Those assumed for the Canadian Shield area of Ontario are 17 kilometres for the granitic layer, and 19 kilometres for the intermediate layer, as found by Hodgson[1]. The densities of the granitic, basaltic, and ultrabasic rock types have been taken as 2·67—2·7, 2·9—3·0, and 3·2 grams per cubic centimetre respectively. The second assumption is that all of the regional gravity anomalies are produced by variations in thickness of either of the crustal layers;

---

[1] Hodgson, J. H.—Analysis of Travel Times from Rockbursts at Kirkland Lake, Ont., Contrib. Dom. Obs., Vol. 1, No. 1.

that is by one layer displacing the other. There is, of course, no proof of this assumption, but there are facts which make it at least reasonable. As will be shown later, there is a marked correspondence between the major anomalies and known Precambrian structural trends, suggesting that the same orogenies produced both the observed surface effects, and the hidden anomaly-producing structures. It is generally believed that the forces of such orogenies acted deep within the crust, in which case they would produce buckling and deformations of the crustal layer, hence the hypothesis that the major anomalies may be taken as expressions of irregularities along the base of either the granitic or intermediate layer. Two unknowns, depth and density contrast, are thus removed from the interpretation.

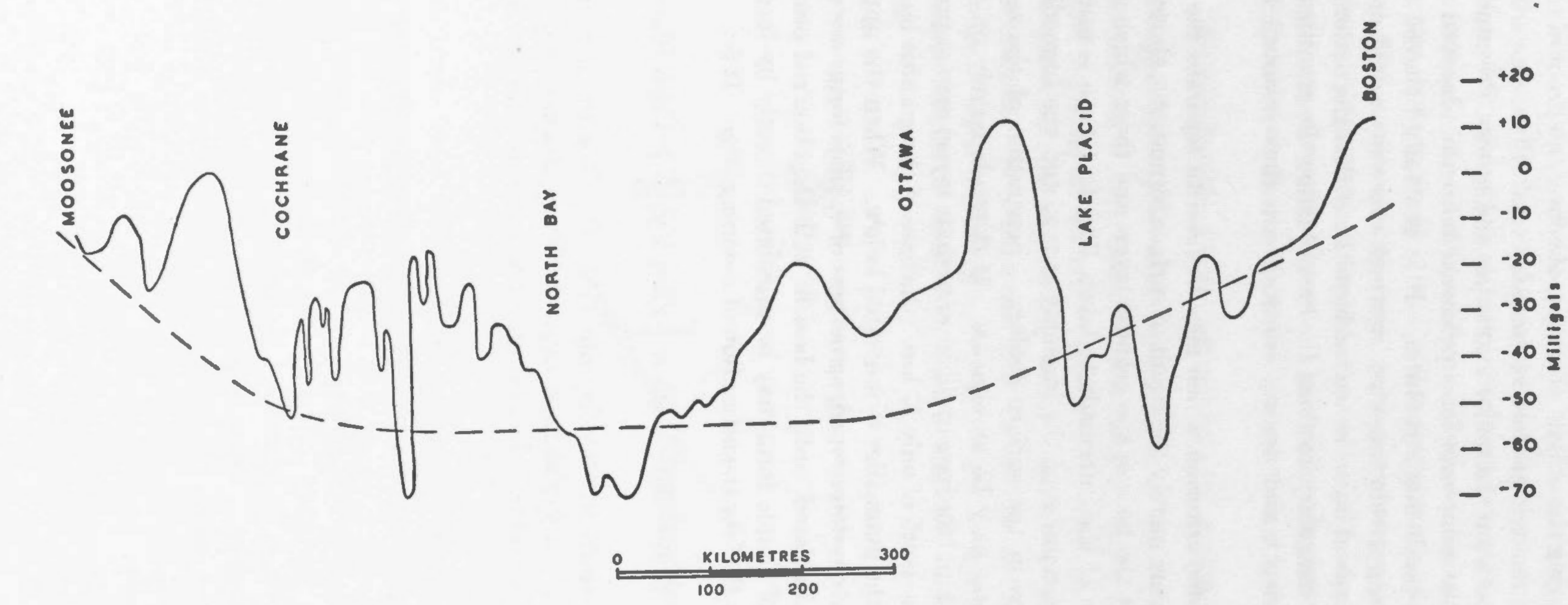
It remains to find some criterion which may be used to separate the anomalies into three classes: those which are merely the result of surface formations, those which could be produced by structures at the base of the granitic layer, and those which represent structures as deep as the base of the intermediate layer. The first type is usually recognized by its local nature, the steepness of the anomaly curve, and the immediate correlation with density distributions in the surface geology. Separation of the second and third types is more difficult, and may be ambiguous. It depends largely on the fact that a structure at a depth of 36 km. (the base of the intermediate layer) cannot produce gradients as steep as a structure at a depth of only 17 km. (the base of the granitic layer). How this can be used to separate the anomalies is indicated below. When the appropriate depth for the cause of an anomaly is determined, structures of various forms are assumed at this depth, and their effects calculated, until the best fit with the observed profile is obtained. The effect of structures of simple form may be calculated directly by formulae. One of the most useful of these is that for the attraction of a sloping step. It is:

$$\Delta g = 2G(\rho_2 - \rho_1)\ [T\Phi_2 - t\Phi_1) - x \sin\alpha \left[\sin\alpha \log_e \frac{r_2}{r_1} + \operatorname{Cos}\alpha\,(\Phi_2 - \Phi_1) \right]$$

where the symbols are shown in the diagram (Fig. 1). For more irregular bodies, a segment chart is employed. By placing a cross-section of the assumed body, drawn to scale, over such a chart, the anomaly for stations at any distance may be determined, and a profile drawn.

STRUCTURES AT THE BASE OF THE INTERMEDIATE LAYER

In the accompanying diagrams (Figs. 2 and 3) are shown rather highly condensed profiles, along two long traverses. One reaches from the Atlantic Coast across the Appalachians, through Ottawa to Moosonee on James Bay. The second runs westward from Winnipeg to the Rockies. There would appear to be in both these profiles very broad, gradual trends upon which the smaller (but nevertheless regional) anomalies are superimposed. In the first profile, the trend is in the form of a gradual decrease inland from the Atlantic, and also from James Bay. The second profile shows an obvious decrease west from Winnipeg. Possibly, these broad effects represent a thickening of the intermediate layer under the interior of the continent, and a further thickening under the Rocky Mountains. Certainly they appear to be of an order of magnitude broader than any of the anomalies attributed to the granitic layer, which would suggest a deeper



GRAVITY PROFILE
BOSTON—MOOSONEE

(The profile from Boston to Ottawa is based on observations by Dr. C. P. Woollard.)

FIG. 2. Gravity profile—Boston-Moosonee.

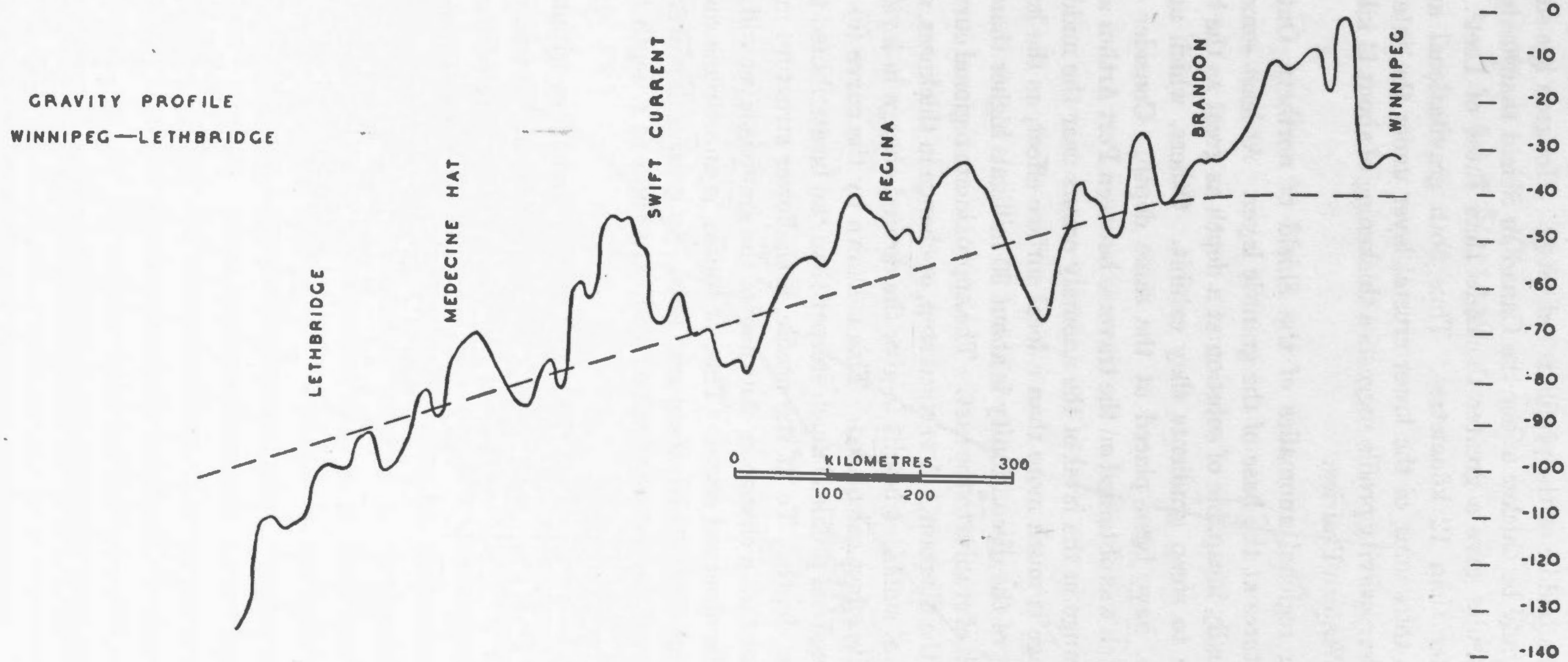


FIG. 3. Gravity profile—Winnipeg-Lethbridge.

cause for them. Adopting this explanation, a thickening of the intermediate layer of about 5 km. near the middle of the profile is indicated. Hodgson has suggested that the intermediate layer may be thicker under the Canadian Shield than under New England, as certain of his results gave a greater thickness than those of Leet[2]. The difference amounted to greater than 12 kilometres. Thus both gravitational and seismological methods indicate a thickening of the lower crustal layer under the interior of northern Ontario. The western gravity profile suggests a thickening of about 11 kilometres between Manitoba and the Western Prairies.

The remaining regional anomalies of the Shield of northern Ontario have been attributed to structures at the base of the granitic layer. At least some of these can be shown to be practically incapable of solution at a depth as great as the base of the intermediate layer, due to steep gradients they exhibit. Others, which appear to form a pattern with these, have been placed at the same depth. Consider first the profile shown in Fig. 4, which was obtained on the traverse between Port Arthur and Dryden, Ont. A rather abrupt change in the level of the anomaly occurs near the middle of the profile. Obviously the change is much more than a local surface effect, as the level over a broad area of granite west of the discontinuity is about 30 milligals higher than the level over a similar broad stretch of granite to the east. The approximate regional curve is indicated by the solid line (b) in the diagram. A vertical step, or change in thickness, at the base of the intermediate layer, of sufficient height to give the desired change in level of the anomaly was assumed, and its effect calculated. This is shown by the curve (c). It is apparent that the observed regional profile is much steeper than can be attributed to even a vertical step at such a great depth. To fit the profile, a shallower structure must be assumed. It will be shown later that a change in thickness of the granitic layer will give a very close approximation to the observed curve. This, of course, is an extreme case; not all of the anomalies of this type exhibit such steep gradients. In general, however, closer approximation to the observed curves are obtained with structures at a depth of 17 kilometres, rather than 36 kilometres.

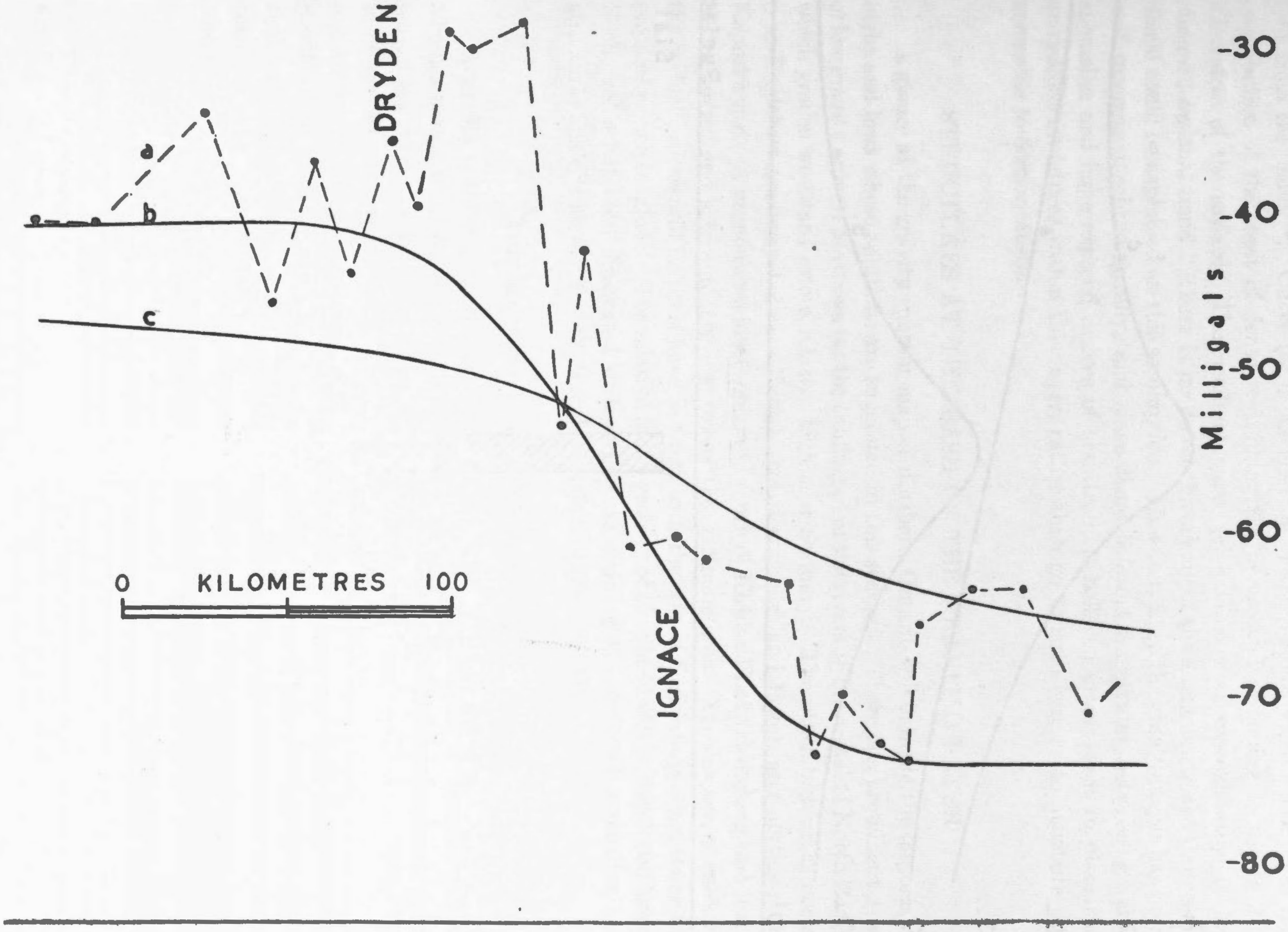
The conclusion reached is that the major gravity anomalies within the area under study are best explained by structures within the granitic layer. It would appear that the effects of variation in thickness of the intermediate layer are only noticeable in traverses covering a significant portion of the continent. In the latter case, a very gentle decrease in gravity is noted as one proceeds inland from the Atlantic, or from James Bay, or toward the western mountains. A thickening of the intermediate layer under the interior of the continent is offered as an explanation of these trends.

In this connection, the work of Schwinner [3] in the Alps may well be mentioned here. Schwinner attempted to explain certain major Bouguer anomalies on the basis of variations in crustal thickness, adopting an average thickness of 50 kilometres. He met precisely the situation outlined above, in that the observed profiles had gradients which could not be approximated by any structure at such a great depth. Instead of attempting a solution at a lesser depth, he pictured the situation illustrated in Fig. 5. Immediately above the

---

[2] Leet, L. D.,—Trial Travel Times for Northeastern America, Bull. Seis. Soc. Am., Vol. 31, pp. 325-334, 1941.

[3] Schwinner, R.,—"Geophysikalische Zussamenhänge Zwischen Ostalpen und Bomischen Masse"—Beiträge zur Geophysik, Vol. 23, 1929.



(a) Observed Profile.
(b) Suggested Regional Curve.
(c) Effect of a vertical step of 5 km. at a depth of 40 km.

FIG. 4. Gravity profile—Ignace-Dryden.

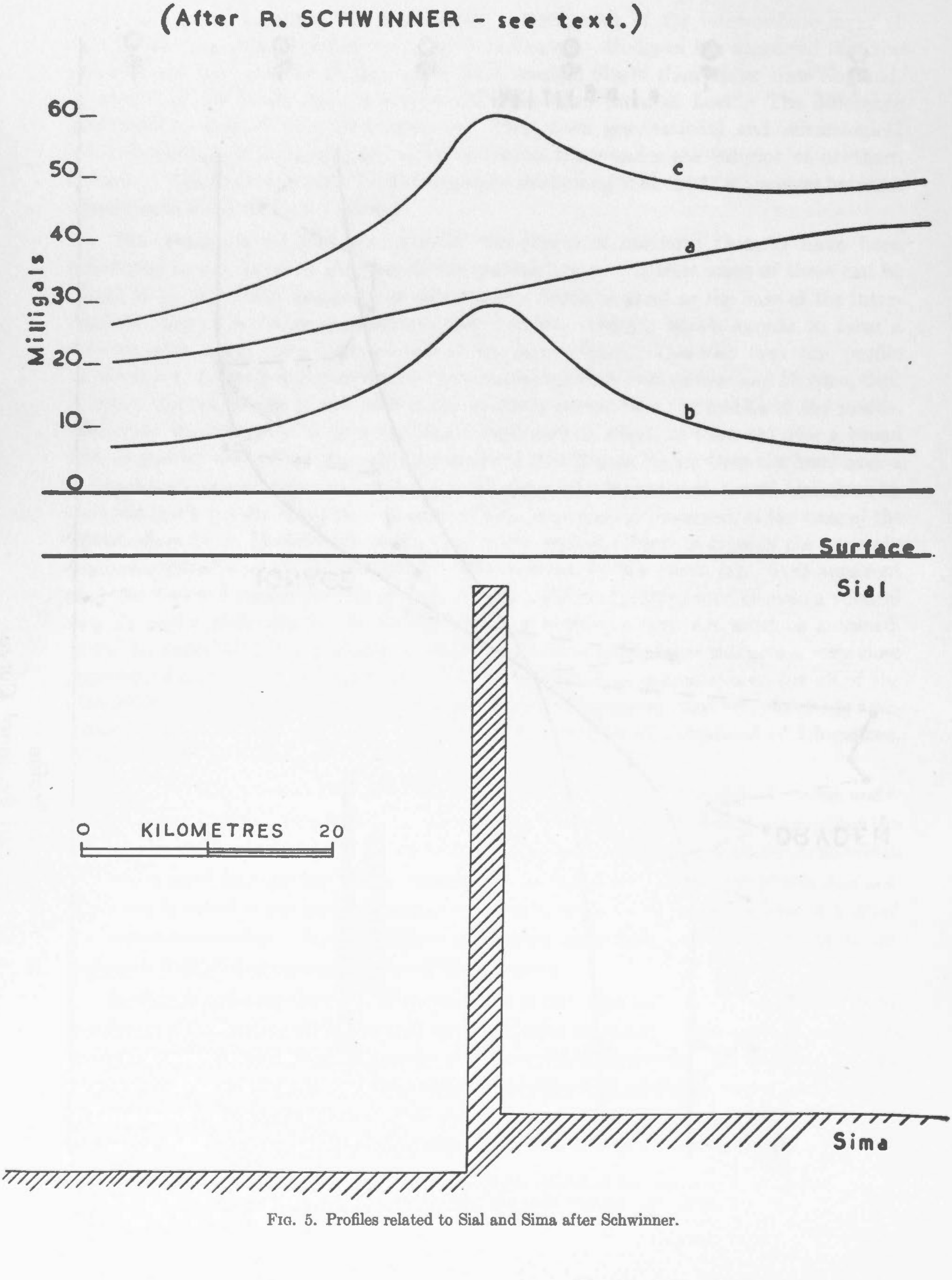


FIG. 5. Profiles related to Sial and Sima after Schwinner.

step-like thickening of the "sial"* a great fissure has formed, and become filled with basic rock from the "sima"*. Curve (*a*) is the effect of the step alone, while curve (*b*) is the contribution of the sheet of dense rock filling the fissure and extending to within 2·5 kilometres of the surface. The resultant curve (*c*) gave a good approximation to his observed regional trend. There is no doubt that many of the anomalies of the Canadian Shield could be explained on this assumption. However, since the granitic layer has been well recognized seismologically, and since there is some correlation between gravity anomalies and large exposed masses of granite, it is believed more direct to place the anomalous structures within this layer, rather than go to such lengths to attribute the anomalies to deeper causes.

STRUCTURES AT THE BASE OF THE GRANITIC LAYER

A glance at the gravity contour map of northern Ontario will indicate the important highs and lows whose solutions are suggested in this section. There is a prominent area of low gravity around Mattawa (at the confluence of the rivers 35 miles east of North Bay), which grades westward into a relative high near Sudbury. The other high areas occur near Englehart (midway between New Liskeard and Kirkland Lake), and northeast of Kapuskasing. A pronounced low is observed south of Kirkland Lake stretching east from Matachewan, and a less intense low covers the Timmins area. Profiles across each of the major features will be considered in turn, with the aim of first interpreting them on physical principles alone. The relation to the geology of the Shield will be developed later. Each profile has been illustrated with a diagram showing the observed anomalies, the structures finally adopted, and the calculated effect of the structure.

THE MATTAWA LOW AND THE SUDBURY HIGH

A profile running generally east-west from near Chalk River to Thessalon (about 30 miles west of Blind River)† crosses both the low near Mattawa, the Sudbury high, and a second low west of this high, as shown in Fig. 6. The regional curve is apparently the resultant effect of a central anticlinal thinning of the granitic layer with synclinal thickening, both east and west. Thus, the Mattawa low can be explained by a thickening of about 4 km. along a strip 90 kilometres wide. As indicated by the contour map, the strike of the structure is Northeast to Southwest. The central anticline indicates that the granitic layer is about 2·5 km. thinner than normal under the Sudbury district, while west of this, in the Blind River area, there is a second thickening.

---

* These terms are used by Schwinner, who apparently considered the sial to include the complete crust. They have been avoided elsewhere in this paper in favor of the more modern layer terminology.

† With the exception of those between Cochrane and Moosonee all stations referred to in this publication are located on provincial highways. In cases where there may appear to be some doubt regarding the location of a station it is suggested that the reader consult the Map Indicating Main Automobile Roads Between United States and Canada published by the Canadian Government Travel Bureau of the Department of Trade and Commerce or the official road maps of the Provinces of Ontario and Quebec. The geology of the region is covered by the Lake Huron, Lake Nipigon, and Kenora sheets on a scale of eight miles to an inch and by other maps of the Geological Survey mentioned in the text. It is suggested that these may be consulted with advantage by the reader in perusal of the paper.

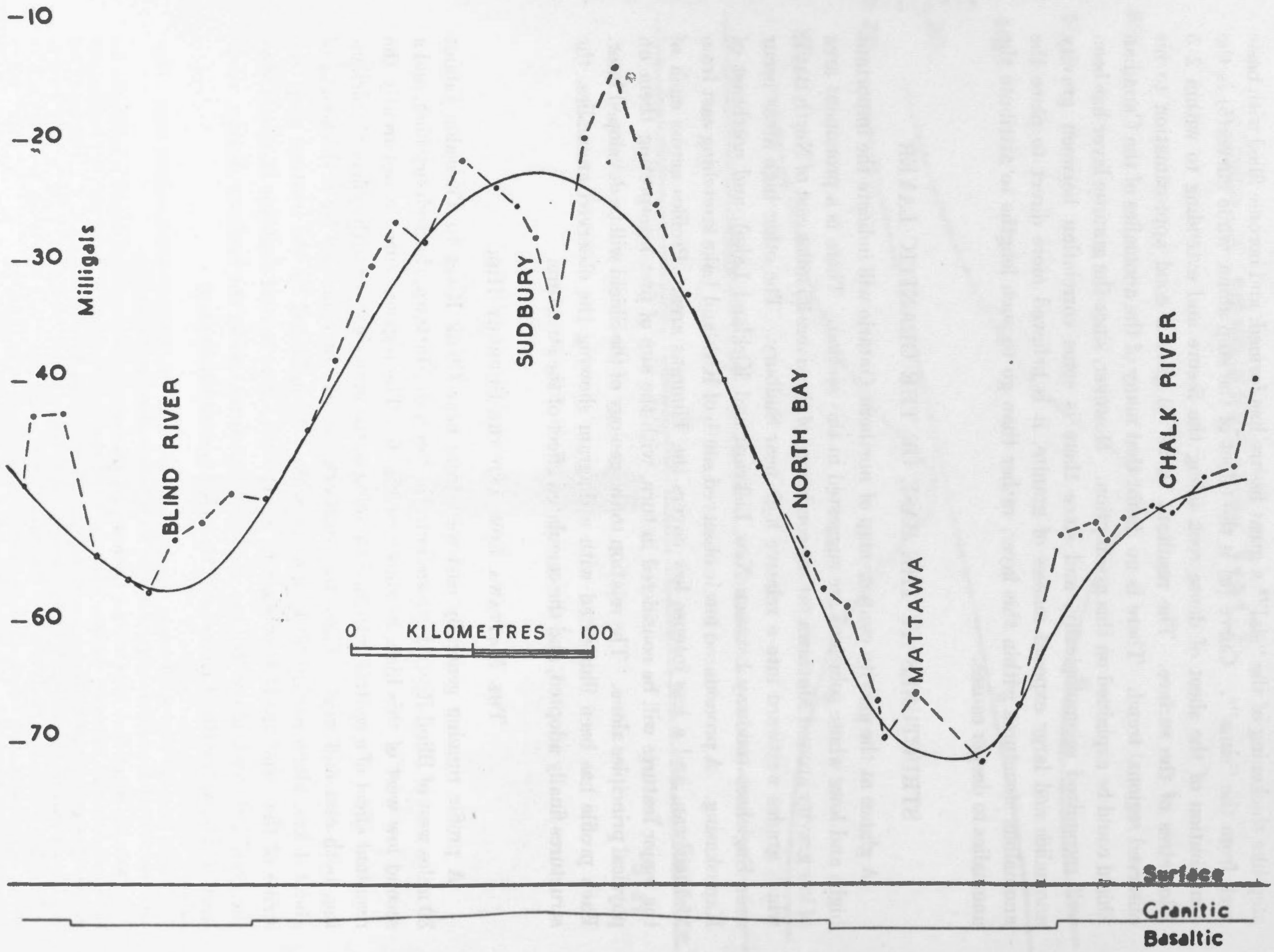


FIG. 6. Mattawa-Sudbury profile.

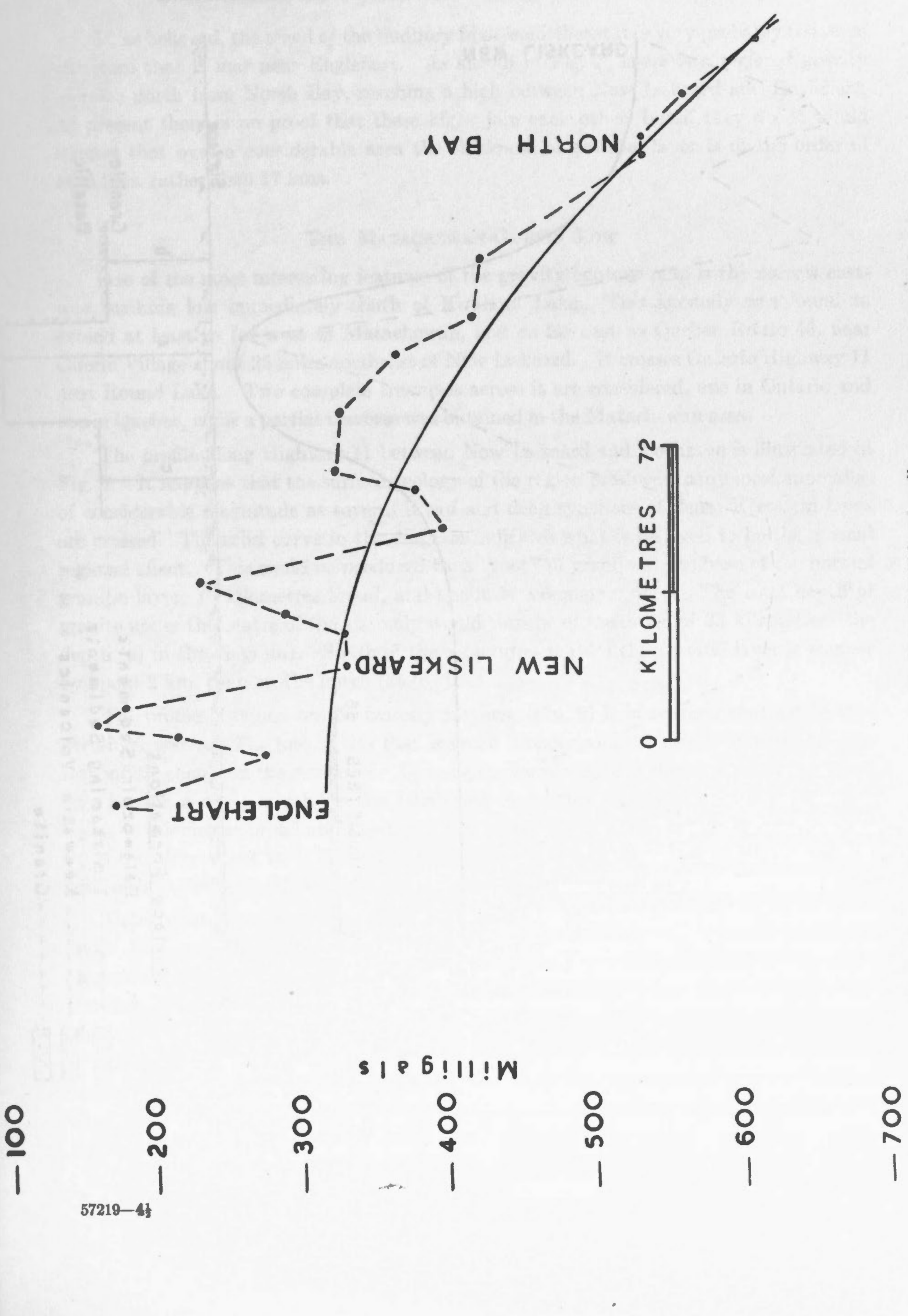


FIG. 7. North Bay-New Liskeard profile.

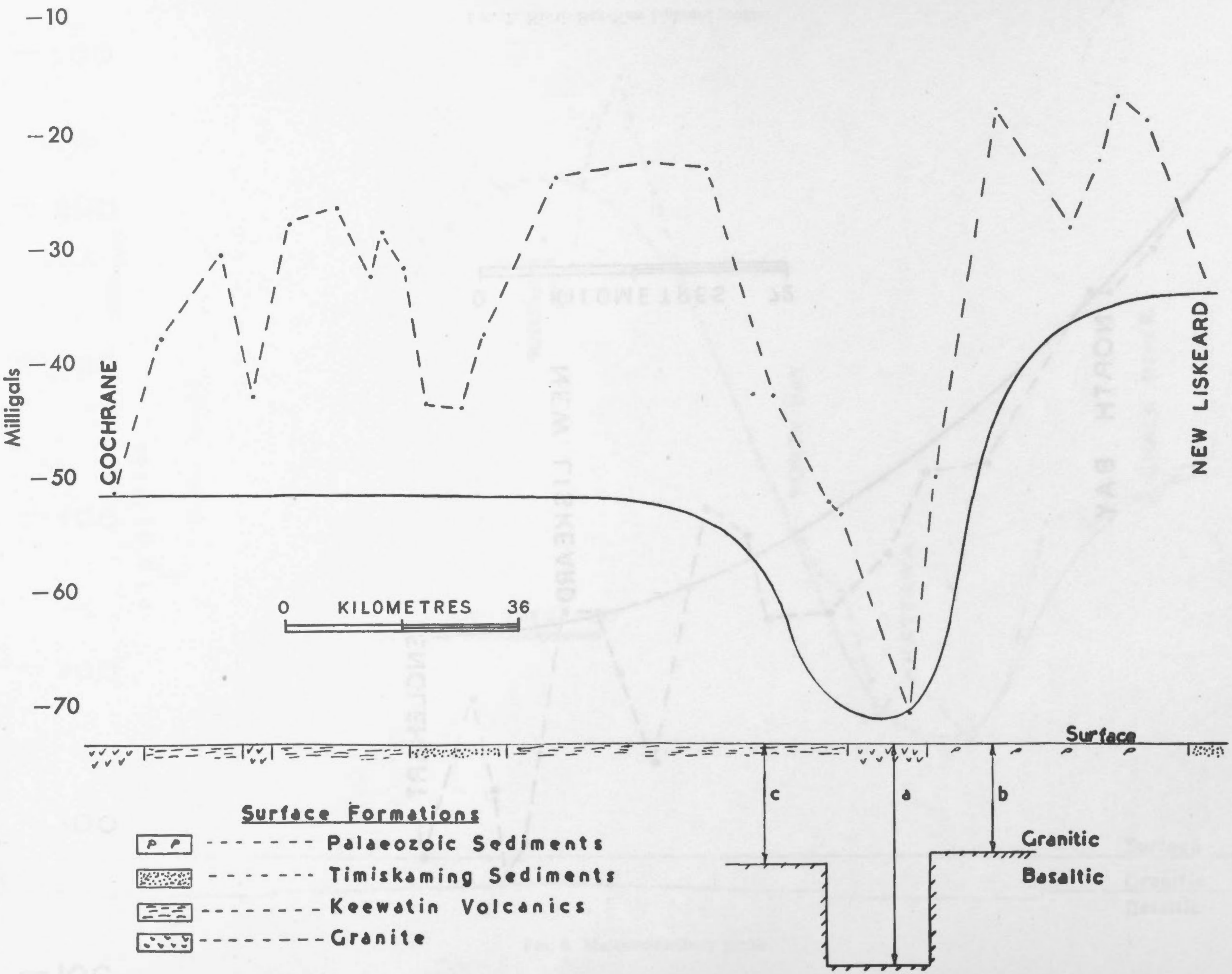


FIG. 8. New Liskeard-Cochrane profile.

If, as believed, the trend of the Sudbury high is northeast it is very probably the same structure that is met near Englehart. As shown in Fig. 7, there is a regional gravity increase north from North Bay, reaching a high between New Liskeard and Englehart. At present there is no proof that these highs join each other, but if they do, it would suggest that over a considerable area the thickness of granitic layer is of the order of 14·5 kms. rather than 17 kms.

THE MATACHEWAN-GUERIN LOW

One of the most interesting features of the gravity contour map is the narrow east-west striking low immediately south of Kirkland Lake. This anomaly was found to extend at least as far west as Matachewan, and as far east as Quebec Route 46, near Guerin Village about 25 miles northeast of New Liskeard. It crosses Ontario Highway 11 near Round Lake. Two complete traverses across it are considered, one in Ontario and one in Quebec, while a partial traverse was obtained in the Matachewan area.

The profile along Highway 11 between New Liskeard and Cochrane is illustrated in Fig. 8. It happens that the surface geology of the region produces many local anomalies of considerable magnitude as several broad and deep synclines of dense Keewatin lavas are crossed. The solid curve in the diagram indicates what is believed to be the normal regional effect. This could be produced by a "root" of granite at the base of the normal granitic layer, 16 kilometres broad, and about 16 kilometres deep. The total depth of granite under the centre of the anomaly would thus be of the order of 33 kilometres (the depth (a) in the diagram). South of the structure (at (b)) the granitic layer is thinner by about 2 km. than on the north (at (c)).

The profile obtained on the easterly traverse (Fig. 9) is in marked contrast to that described above. The low in this case is much broader and shallower, indicating a corresponding change in the structure. Once again, certain surface effects must be smoothed out, leaving a curve which can be attributed to a synclinal thickening of the granitic layer, 48 kilometres broad and about 8·5 kilometres deep. The depth of granite rock at (*a*) is therefore about 25·5 kilometres (as compared to 33 kilometres to the west). The granitic layer immediately south of the structure (*b*) is thinner than it is on the north (*c*).

Unfortunately a complete profile across the low was not obtained in the Matachewan area. However, the profile from Elk Lake to Matachewan (Fig. 10) would suggest a structure as deep, and as steepsided, at least on the south side, as that met on the central traverse. In fact, the greatest negative Bouguer anomaly of the entire region is that at Matachewan townsite.

The Matachewan-Guerin low is thus conceived as representing a relatively narrow, east-west striking thickening of the granitic layer. A strike length of at least seventy miles is suggested, but the structure varies in character along its length, apparently becoming deeper and narrower toward the west.

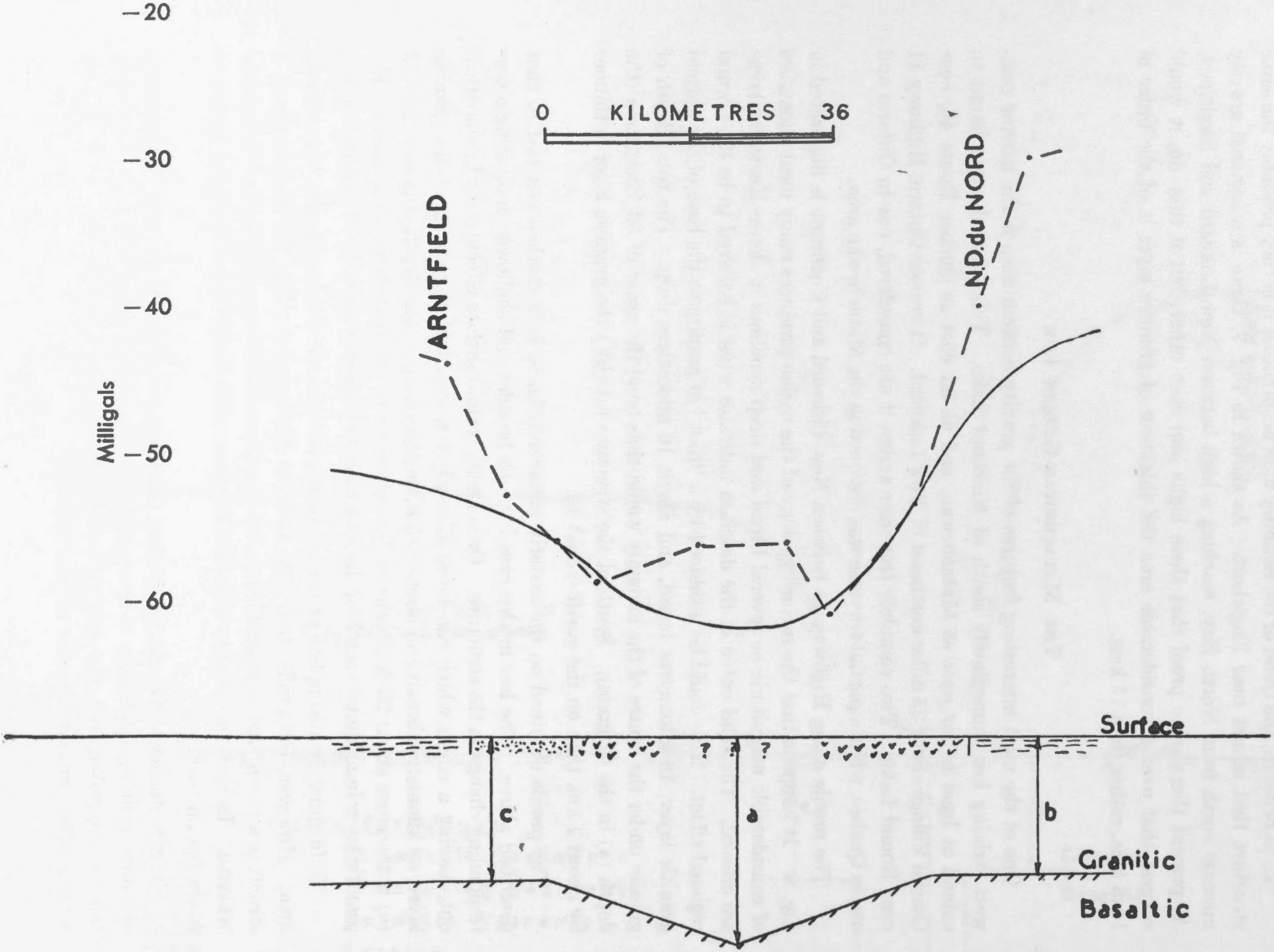


FIG. 9. Notre Dame du Nord-Arntfield profile.

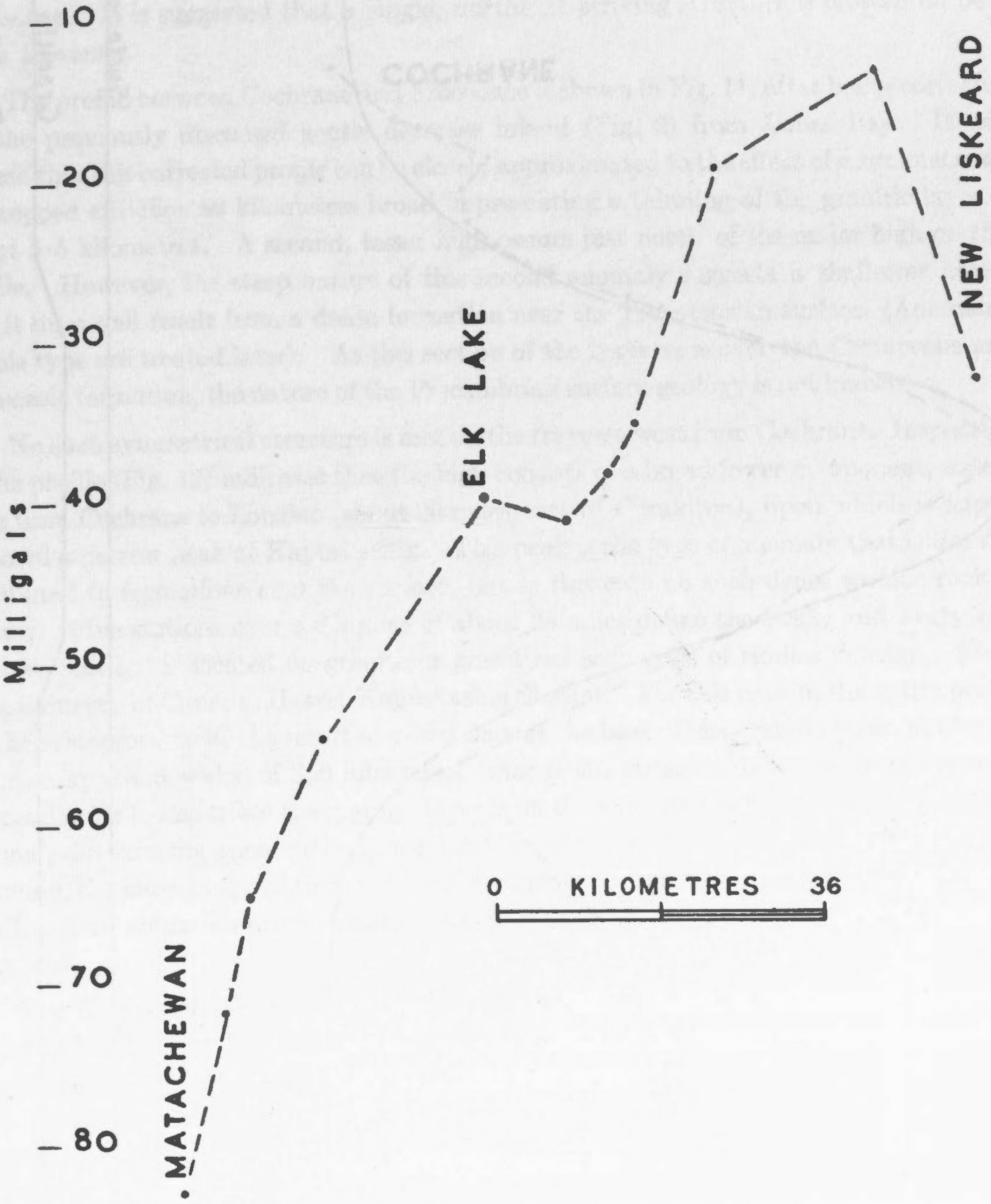


FIG. 10. New Liskeard-Matachewan profile.

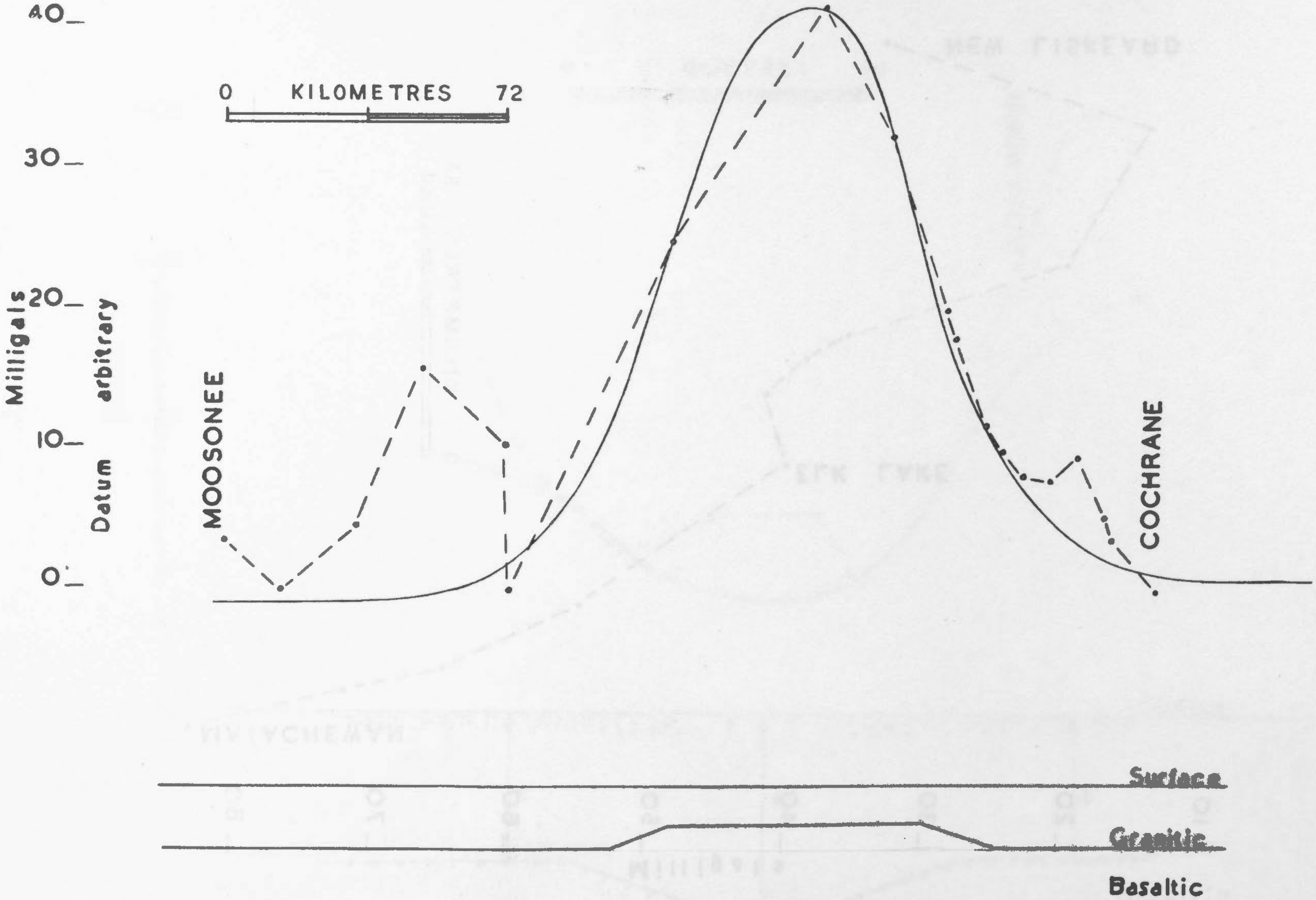


FIG. 11. Cochrane-Moosonee profile.

THE KAPUSKASING-FRASERDALE HIGH

The location and general trend of this feature are indicated by the anomaly map. On the profile west from Cochrane, the peak of the high was found to be near Kapuskasing. Subsequently, a similar maximum was observed at Fraserdale, between Cochrane and Moosonee. It is suggested that a single, northeast striking structure is crossed on both these traverses.

The profile between Cochrane and Moosonee is shown in Fig. 11, after being corrected for the previously discussed gentle decrease inland (Fig. 2) from James Bay. It will be seen that this corrected profile can be closely approximated to the effect of a symmetrical, flat-topped anticline 80 kilometres broad, representing a thinning of the granitic layer of about 5·5 kilometres. A second, lesser high occurs just north of the major high on this profile. However, the steep nature of this second anomaly suggests a shallower cause, and it may well result from a dense formation near the Precambrian surface. (Anomalies of this type are treated later). As this section of the traverse is over the Cretaceous and Palæozoic formation, the nature of the Precambrian surface geology is not known.

No such symmetrical structure is met on the traverse west from Cochrane. Inspection of the profile (Fig. 12) indicates that the high consists of a broad lower component, extending from Cochrane to Longlac (about 20 miles east of Geraldton), upon which is superimposed a narrow peak at Kapuskasing. This peak is the type of anomaly that is usually attributed to formations near the surface, but in this case no such dense surface rock is known. Five stations over a distance of about 25 miles define the peak, and every one of these stations is located on granite or granitized sediments of similar density. (Geological Survey of Canada: Hearst-Kapuskasing Sheets). For this reason, the entire profile has been assumed to be the result of a structure at the base of the granitic layer, as shown. Over an apparent width of 350 kilometres (that is the structure is probably not crossed perpendicular to its strike) the granitic layer is on the average 2·5 kilometres thinner than normal, the thinning apparently decreasing toward the west. In addition to this general thinning, the basic material from the basaltic layer is assumed to have risen an additional 8 kilometres along a narrow fissure near Kapuskasing, producing the gravity high in that area.

The Kapuskasing-Fraserdale high may, therefore, be taken as indicating a northeast trending band of thinned granitic layer. Like others of the major structures suggested, it must be assumed to change in character along its length.

THE PORT ARTHUR LOW

What is termed the Port Arthur low is a large area, as yet not completely defined, of low Bouguer anomaly near the head of Lake Superior. Along the Trans-Canada Highway, the low is first met west of Nipigon, where the anomaly decreases rapidly. The general level remains low as far west as Ignace, until it rises again in two abrupt

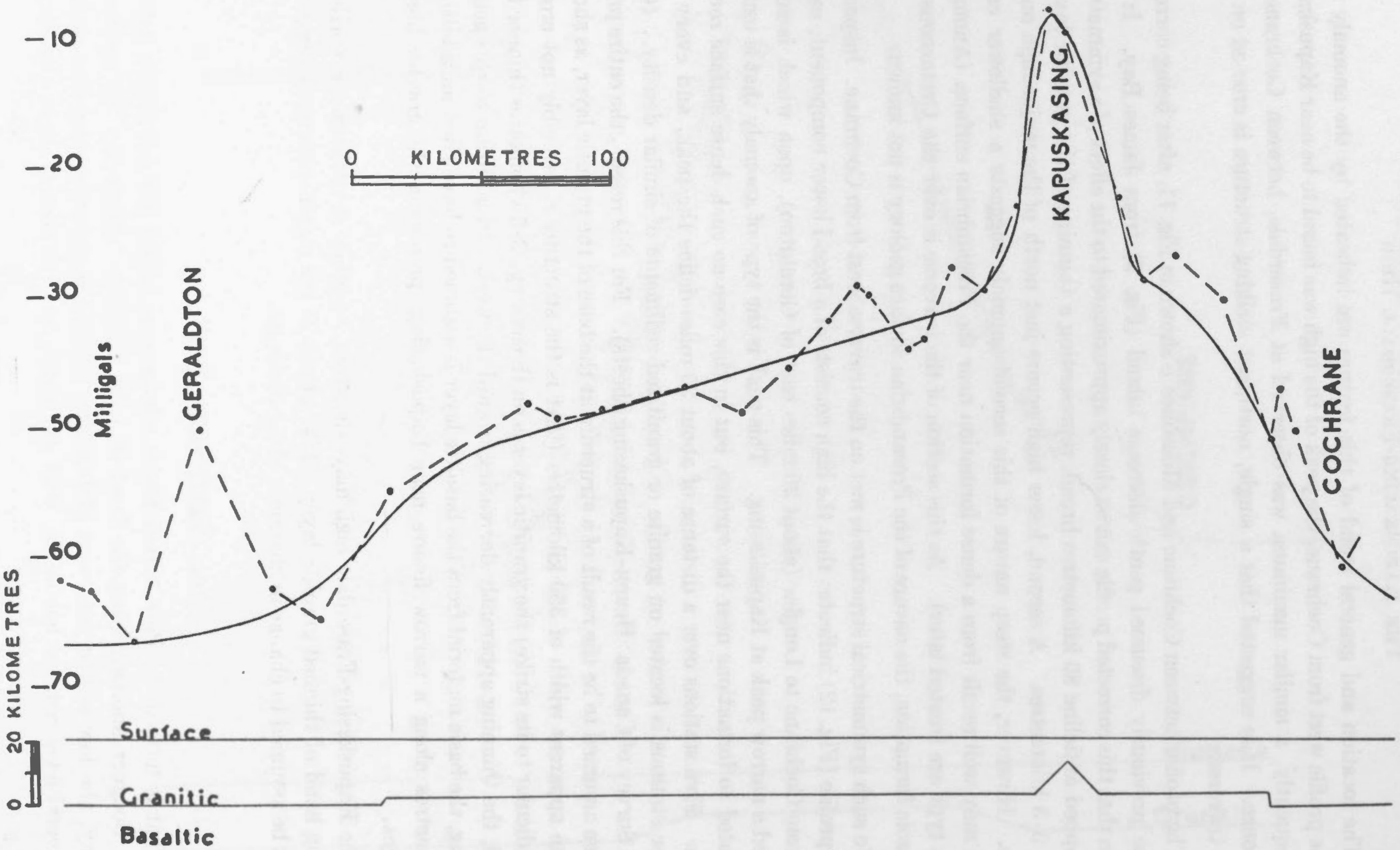


FIG. 12. Cochrane-Geraldton profile.

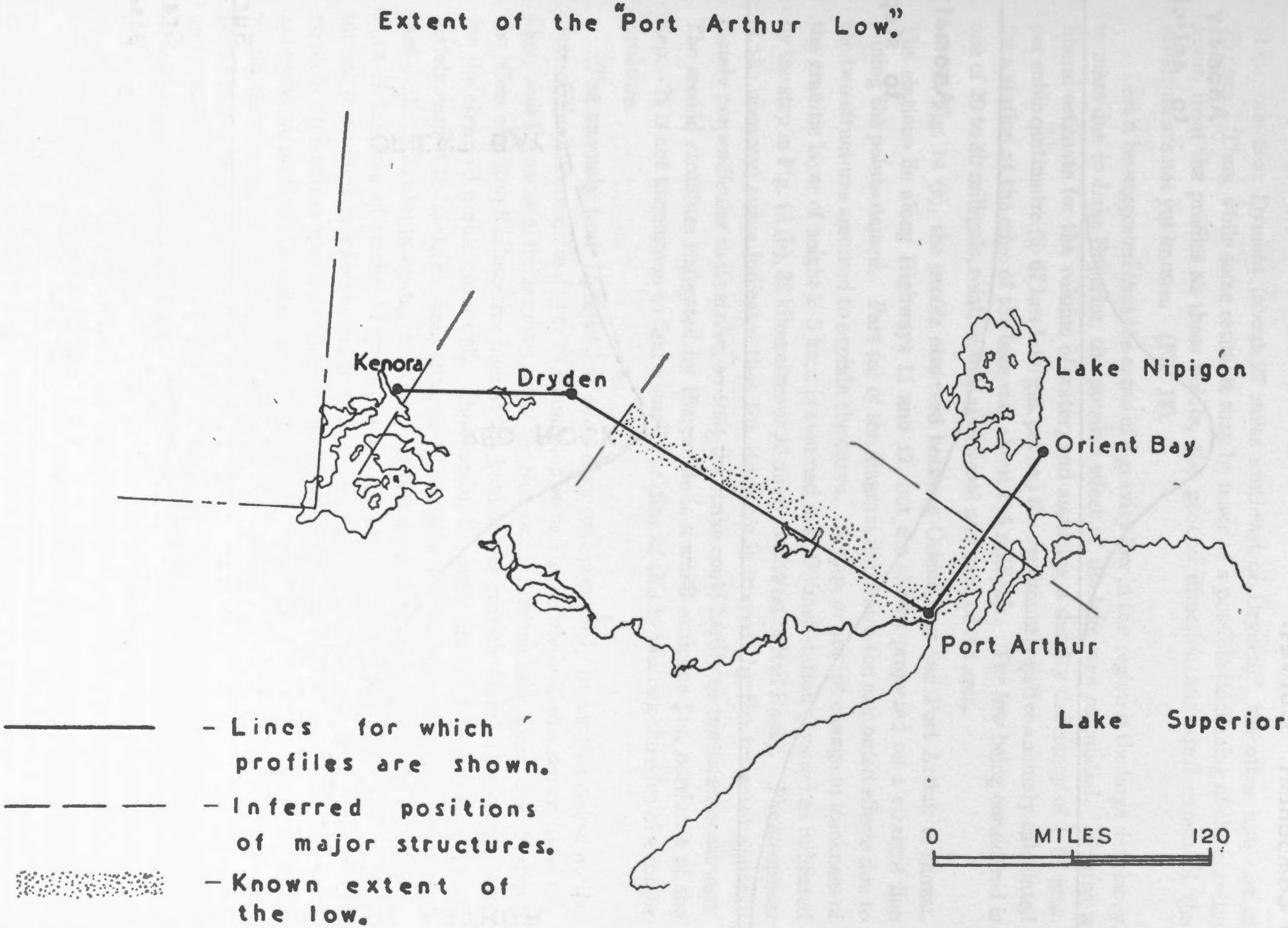
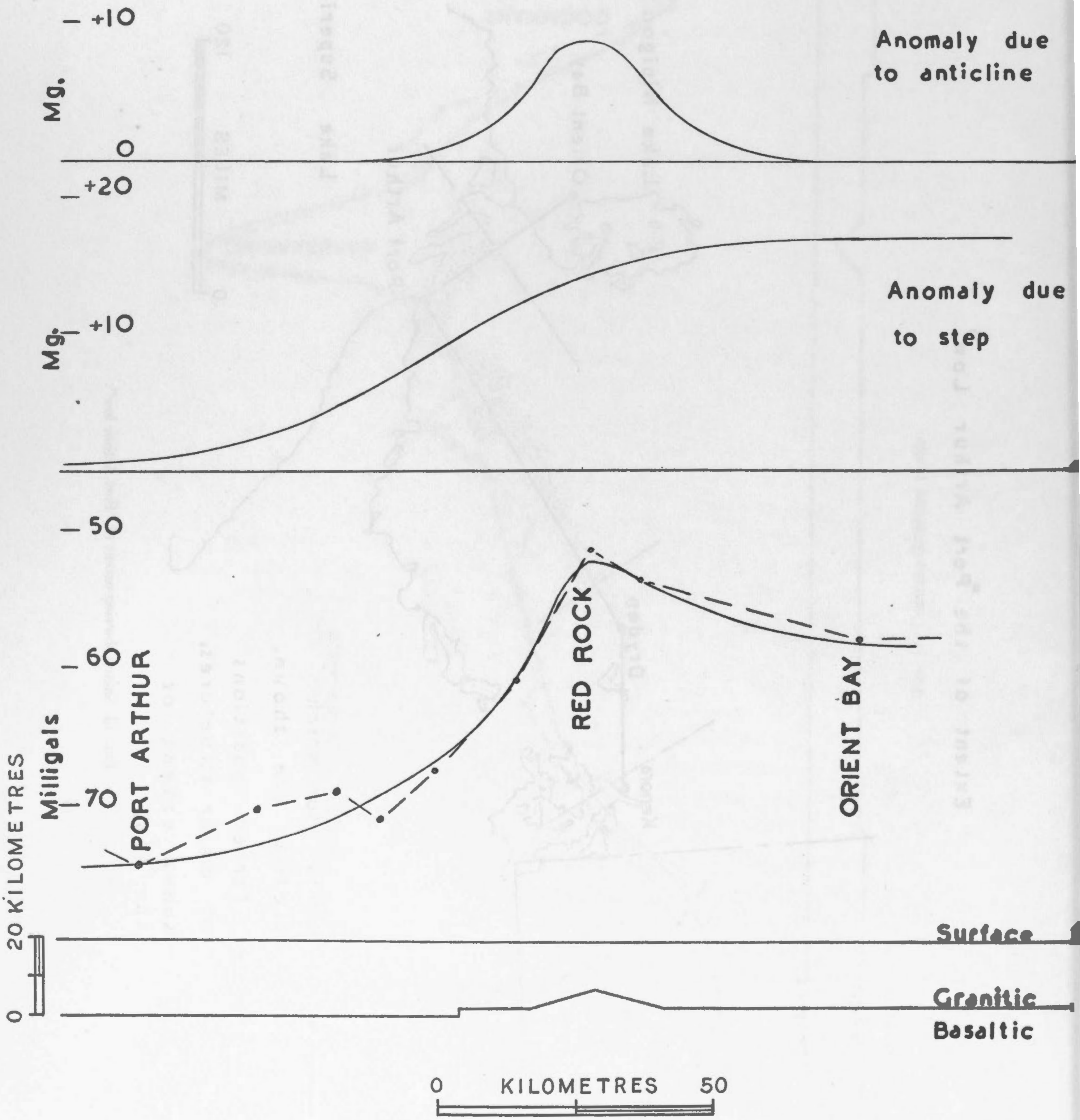


FIG. 13. Sketch showing extent of "Port Arthur low".

(a) Component Curves.



(b) Resultant Calculated Curve and Observed Values.

FIG. 14. Calculated and observed profiles—Orient Bay-Port Arthur.

steps, one near Dyment (about 27 miles southeast of Dryden)*, the other just east of Kenora. Thus, while some estimate may be made of a possible thickening of the granitic layer, from the profiles at these points, the general direction and areal extent of the structure are not yet known. (Fig. 13).

Lest it be suggested that the cause of a gravity low in this region is the large deficiency in mass due to Lake Superior, the possible effect of the lake was calculated. Making a liberal estimate for the volume of water, and assuming a density deficiency of 1·67 gms. per cubic centimetre (2·67 less 1·00 gm. per cc.) the maximum negative anomaly calculated for a station at the edge of the lake was about 1·5 milligals. The low being considered is one of 20 to 30 milligals, relative to stations east and west of the area.

In Fig. 14 (*b*), the profile observed between Orient Bay and Port Arthur is shown. The stations lie along Highways 11 and 17, but are shown projected on a straight line joining the points named. Part (*a*) of the diagram illustrates the computed effects due to the two structures assumed to explain the curve. A step, or abrupt change in thickness of the granitic layer of height 2·5 km., is assumed near Ouimet station (located as indicated by the step in Fig. 14 (b), 32 kilometres or 20 miles southwest of Red Rock). The steepness of the observed curve indicates that the structure is crossed (by the traverse) approximately perpendicular to its strike, so that the strike could hardly be northeast-southwest. The second structure suggested by the profile is a small anticline just northeast of the step. It is not uncommon to find a small buckling of this type along the edge of a major structure.

The anomaly near Dyment has been discussed previously under Structures at the Base of the Intermediate Layer in connection with Fig. 4, where it was shown to be unlikely that the cause of the anomaly lay at the base of the intermediate layer. Fig. 15 shows the effect of a step 5 kilometres high at the base of the granitic layer, which apparently fits the observed profile quite well. Once again, the structure must be crossed approximately normal to its strike, suggesting that the strike of this step is more northeast than east-west. The abrupt change in gravity at this point thus represents the northwesterly limit of the area of thickened granitic layer about Port Arthur. While it is probably unwise to attempt to infer the limits of this area from the results of only two traverses, a possible explanation would be that a line between Dyment and Ouimet represents the approximate northern boundary of the thickened region. The general strike of the region would then be east-west (but because of irregularities, the northern boundary may in places run northeast, as at Dyment), and the southern boundary of the region, as yet undetected, may lie somewhere south of Port Arthur.

The second change in level of the anomaly, near Kenora, represents a further thinning of the granitic layer. A step about 1·8 kilometres high gives the curve shown (Fig. 16). Presumably the granitic layer remains thinner than normal westward into Manitoba.

---

* The gravity observation was taken on the highway at the intersection in the little settlement about 2 miles south of Dyment railway station. On the provincial highway map, the settlement is designated by the name Borups Corners and by Dyment on the Travel Bureau maps. It probably should be Borup Corners as marked on the road signs, after Mr. Andrew Borup, the first settler, who came there in 1917.

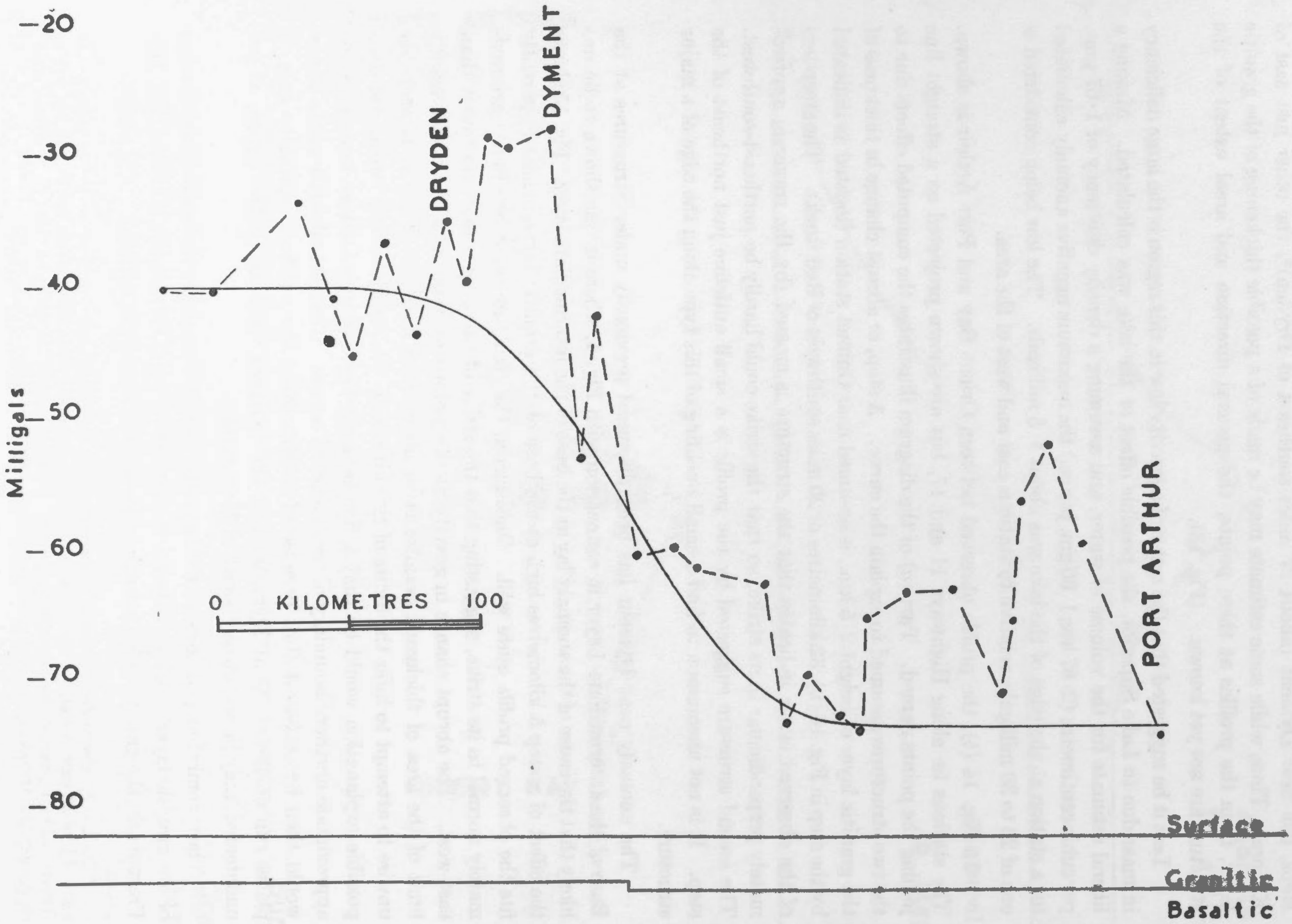


FIG. 15. Port Arthur-Dryden profile.

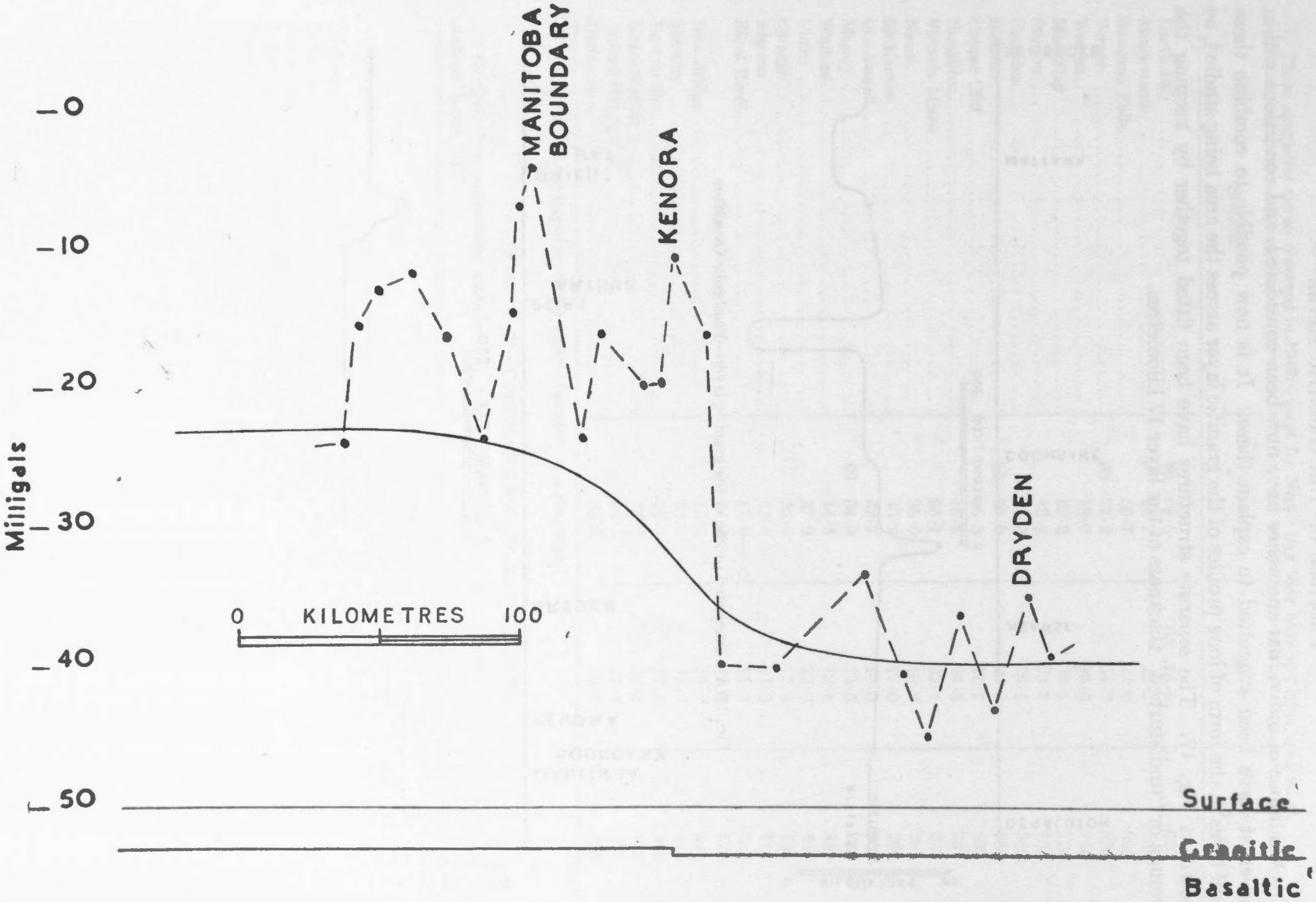


FIG. 16. Dryden-Manitoba boundary profile.

PROFILES OF THE GRANITIC LAYER

A number of individual anomalies have now been considered, and conditions within the crust have been suggested to explain these. It is now possible to combine these structures in the form of long profiles of the granitic layer across the area being studied, as shown in Fig. 17. The separate structures have been fitted together by keeping the average or "undisturbed" thickness of the layer 17 kilometres.

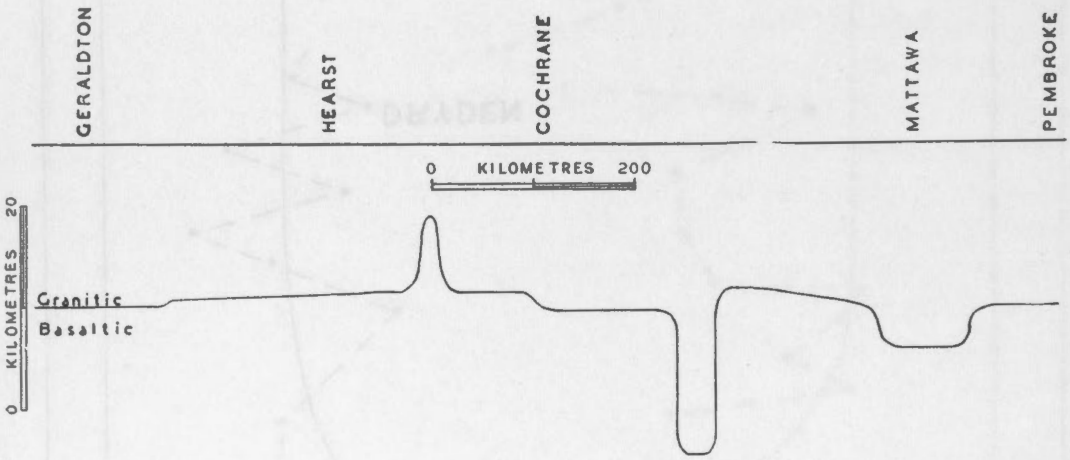


FIG. 17(A). Suggested profile of the granitic layer—Pembroke-Geraldton

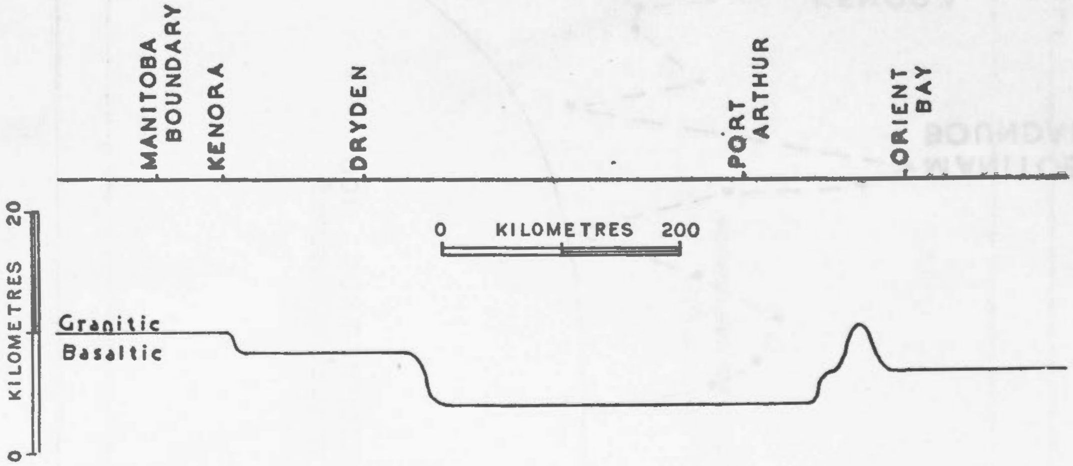


FIG. 17(B). Suggested profile of the granitic layer—Orient Bay-Kenora.

TABLE 1 (*a*)—NORTH BAY-SUDBURY TRAVERSE

These anomalies are as observed in 1945; except for North Bay they have not been readjusted.

Station	Longitude °	'	Latitude °	'	Bouguer Anomaly 10^{-4} cm/sec^2
North Bay	79	28·0	46	18·9	−523
Meadowside		44·7		22·2	464
Sturgeon Falls		55·7		22·0	395
Verner	80	07·2		24·7	326
Warren		18·7		26·6	245
Markstay		32·2		29·1	136
Stinson		42·1		30·7	194
Coniston		51·0		29·1	340
Sudbury	81	00·0		29·8	280
Copper Cliff		04·5		27·7	252
Naughton		10·8		24·3	241
Victoria Mines		23·1		23·4	213
Nairn		35·0		19·8	283
McKerrow		45·3		17·0	262
Webbwood		52·7		16·0	301
Massey	82	04·9		12·5	368
Walford		14·5		12·1	439
Cutler		27·6		12·0	489
Spragge		39·6		12·3	490
Algoma		48·6		11·0	516
Blind River		57·0		11·0	533
	83	06·0		12·9	576
Iron Bridge		13·3		16·7	565
Sowerby		23·3		17·7	544
Nestorville		36·2		17·3	425
Bruce Station		45·9		19·0	452
Jacks Point		46·7		17·7	437
Desbarats		55·4		20·7	422

All anomalies are negative except where indicated by a plus sign.

TABLE 1 (*b*)—COCHRANE-NORTH BAY TRAVERSE

Original observations were made in 1946, but the anomalies have been corrected after the repetition of certain stations during 1947.

Station	Longitude °	'	Latitude °	'	Bouguer Anomaly 10^{-4} cm/sec^2
Cochrane	81	00·5	49	03·9	−513
Holland	80	51·4	48	52·0	427
Devonshire		49·3		49·0	276
Nellie Lake		48·0		45·6	262
Porquis		46·8		42·4	324
Kelso		44·7		40·7	280
Monteith		40·6		38·6	310
Val Gagne		38·2		36·9	428
Matheson		28·0		32·0	365
Ramore		19·3		26·3	228
Bourkes		13·6		17·4	217
		15·4		13·8	216
		11·5		06·0	315
Swastika		06·0		06·4	409
		00·2		02·0	501
		00·7		00·6	509
		00·8	47	56·4	683

TABLE 1 (*b*)—COCHRANE-NORTH BAY TRAVERSE—*Concluded*

Station	Longitude °	′	Latitude °	′	Bouguer Anomaly 10^{-4} cm/sec^2
Englehart	79	52·1	47	49·5	−150
Earlton		49·0		42·6	252
Thornloe		45·9			190
New Liskeard		40·3		30·6	300
Haileybury		38·4		26·8	300
Cobalt		41·0		23·6	259
Latchford		48·5		19·7	202
		43·6		12·0	366
Goward		47·2		06·5	348
Timagami		47·0		03·9	292
		45·4	46	55·0	297
		48·5		48·1	336
Jct. Routes 11 and 64		50·0		43·0	388
		38·2		35·0	400
		28·0		20·9	520
North Bay		28·0		18·9	523

TABLE 1 (*c*)—GRAVITY STATIONS BETWEEN COCHRANE, ONT., AND THE MANITOBA BOUNDARY

The Anomalies are those obtained in 1946. Certain stations were repeated during 1947 but the adjustments have not yet been made.

Station	Longitude °	′	Latitude °	′	Bouguer Anomaly 10^{-4} cm/sec^2
Cochrane	81	00·5	49	03·9	−513
Hunta		16·4		06·4	407
		20·0		07·6	374
Driftwood		23·0		08·6	413
Smooth Rock Falls		38·0		16·8	304
Strickland		51·4		17·0	268
Gregoire's Mill		57·2		17·2	283
Fauquier	82	02·0		18·5	290
Moonbeam		09·4		20·4	224
Kitigan Sta		18·0		23·0	163
Kapuskasing		25·2		24·7	096
Valrita		32·7		26·6	077
Harty Sta		41·3		28·6	232
Opasatika		52·0		31·5	299
Lowther	83	02·0		33·5	280
Parthia		10·5		35·4	334
Mattice		16·1		36·7	341
Fryatt		20·4		37·5	326
		27·7		39·5	302
Hallebourg	83	31·0	49	40·2	292
Hearst		40·0		41·6	319
		53·1		43·6	356
	84	06·3		44·2	391
		24·5		45·1	369
		32·3		46·5	377
		50·0		46·0	386

TABLE 1 (*c*)—GRAVITY STATIONS BETWEEN COCHRANE, ONT., AND THE MANITOBA BOUNDARY—*Concluded*

Station	Longitude		Latitude		Bouguer Anomaly 10^{-4} cm/sec^2
	°	′	°	′	
Hearst—*Concluded*	85	03·9	49	45·0	−395
		13·5		46·0	384
		55·7		47·1	449
	86	19·1		47·7	563
Longlac		33·0		47·2	525
Geraldton		56·8		43·6	403
	87	16·2		41·6	566
Jellicoe		31·0		41·8	525
Nezah		39·1		40·4	518
Beardmore		57·1		36·0	399
Orient Bay	88	08·0		22·2	578
Nipigon		15·0		00·5	536
(Red Rock)		20·1	48	56·7	516
Hurkett		28·6		51·2	610
Pearl		39·5		40·1	711
Ouimet		35·0		45·2	674
Loon		45·8		38·0	688
Port Arthur	89	13·0		26·3	745
Kaministikwia		35·5		32·3	591
		46·2		34·0	518
		54·3		35·9	559
		55·6		49·4	650
Argon		59·7		52·8	704
Savanne	90	14·8		57·4	626
Upsala		28·0	49	03·2	628
		40·8		03·8	649
		42·5		05·0	734
		48·3		09·4	717
		58·3		14·0	692
	91	04·3		14·8	729
		16·5		16·7	623
		31·6		21·1	611
Ignace		40·0		25·0	615
	92	02·5		30·0	418
		09·0		32·5	528
		19·1		34·9	279
Dinorwic		30·2		41·4	293
Wabigoon		36·2		43·1	285
Barclay		42·5		46·6	395
Dryden		49·9		47·6	350
Oxdrift		58·4		48·6	433
	93	08·0		48·7	365
Gunne		17·3		49·0	451
Vermilion Bay		23·1		51·0	408
		35·0		49·7	335
Hawk Lake		59·8		48·0	403
	94	15·0		43·7	389
		20·0		43·4	162
Kenora		28·4		46·5	137
Keewatin		33·0		45·9	198
		37·7		45·0	199
		48·5		42·7	164
		54·6		43·1	239
Manitoba Boundary	95	09·0		44·4	044

TABLE 1 (*d*)—GRAVITY STATIONS ESTABLISHED DURING 1947 IN THE AREA BETWEEN NORTH BAY AND COCHRANE

Station	Longitude °	′	Latitude °	′	Bouguer Anomaly 10^{-4} cm/sec^2
North Bay, Ont.	79	28·0	46	18·9	−523
(North Bay)		27·0		16·5	576
Trout Mills		24·8		19·7	575
Feronia		19·4		21·7	597
Balsam Crrek		12·1		25.0	642
Little Jocko River		09·7		32·9	610
Jocko River		09·6		36·1	537
Timiskaming, Que. (C.P.R. Sta.)		06·0		43·0	513
Timiskaming (Pend. Sta.)		06·0		43·0	517
Dozois		08·6		50·3	467
Laniel		16·2	47	02·6	480
Fabre		22·0		12·0	356
Baie d'Africain		23·7		14·4	350
Ville Marie		26·5		19·8	352
“		26·1		19·8	344
“		26·7		19·9	356
(Fabre)		21·9		06·6	478
“		22·1		07·1	474
“		22·5		08·4	467
“		22·6		09·1	475
Lavallée River		22·2		10·8	425
(Baie d'Africain)		24·2		15·6	377
(Miron)		25·2		17·6	363
Lorrainville		20·1		21·2	255
(Ville Marie)		26·2		22·1	317
(Guigues)		26·9		24·5	402
(Guigues)		26·2		26·1	386
Guigues		26·2		27·8	275
(Guigues)		26·0		31·9	294
(Notre Dame du Nord)		26·3		35·2	453
Notre Dame du Nord, Que		29·2		35·4	396
Sutton Bay, Ont		35·3		34·0	254
New Liskeard		40·3		30·6	303
(New Liskeard)		49·3		32·2	118
Kenabeek	80	00·0		38·5	185
Mountain Chutes		08·8		39·5	341
Leeville		10·0		39·6	373
(Wabun)		14·6		40·3	404
Elk Lake		20·1		43·5	392
(Elk Lake)		29·8		50·0	542
Matachewan		39·2		56·7	826
(Matachewan)		35·7		57·5	712
“		33·0		55·0	640
(Elk Lake)		13·8		45·2	449
“		16·9		45·1	445
“		10·0		45·4	390
Robillard Lake	80	05·5	47	46·8	323
Charlton		00·6		48·9	305
Englehart	79	52·1		49·5	147
Wawbewawa		53·7		53·0	471
(Wawbewawa)	80	00·8		53·9	686
(Round Lake)		00·8		58·2	683
Swastika		06·0	48	06·4	408
Boston Creek Rd. Jct		00·8		00·8	500

TABLE 1 (*d*)—GRAVITY STATIONS ESTABLISHED DURING 1947 IN THE AREA BETWEEN NORTH BAY AND COCHRANE—*Continued*

Station	Longitude °	′	Latitude °	′	Bouguer Anomaly 10⁻⁴ cm/sec²
Heaslip	79	48·6	47	47·8	−243
Maybrook		45·0		37·5	140
Uno Park		44·9		34·8	159
Haileybury, Ont		37·9		26·9	190
Guerin, Que		15·8		39·9	533
(Guerin)		15·8		45·7	609
(Guerin)		15·7		48·6	559
Riviére Solitaire		14·3		54·8	561
		14·9	48	01·9	586
		15·7		04·7	558
		16·0		08·0	526
Arntfield		15·3		12·1	436
Rouyn		01.9		14.4	345
Noranda		01.3		14.9	341
Noranda		01·3		14·9	342
(Evain)		07·2		14·5	462
Lake Fortune		18·0		11·4	441
Kag Lake, Que		28·5		09·2	506
Cheminis, Ont		31·6		09·8	416
Bear Lake		38·7		07·0	390
Larder Lake Sta		42·5		07·1	421
(Larder Lake)		43·3		05·3	399
(Larder Lake)		42·3		03·4	364
Larder Lake		43·0		05·9	398
Dobie		48·8		07·7	462
King Kirkland		57·3		09·1	466
Kirkland Lake	80	01·9		09·0	427
Dane		00·9		04·1	403
Boston Creek	79	56·4		00·4	473
(Boston Creek)		50·8		00·4	421
(Kirkland Lake)	80	00·6		12·2	308
(Kirkland Lake)		01·5		10·9	323
		14·0		08·5	226
		16·0		11·7	256
Yorkston		14·2		22.0	258
		25·2		27·2	289
Shillington		40·8		32·5	336
		51·4		32·9	530
Timmins	81	20·0		28·6	501
Schumacher		17·7		28·6	477
South Porcupine		11·8		28·4	517
Porcupine		09·5		30·0	518
Pamour		07·2		31·6	504
Hoyle		03·4		33·1	527
Drinkwater		00·5		35·2	552
Connaught	80	55·6		37·0	506
McIntosh Springs		52·0		38·8	401
Alexo		49·0		40·3	366
Iroquois Falls		40·7		45.9	198
Porquis		46·8		42·4	324
		58·6		55·1	308
	81	00·5	49	00·2	378
Cochrane		00·6		03·6	513

TABLE 1 (*d*)—GRAVITY STATIONS ESTABLISHED DURING 1947 IN THE AREA BETWEEN NORTH BAY AND COCHRANE—*Concluded*

Station	Longitude		Latitude		Bouguer Anomaly 10^{-4} cm/sec^2
	°	′	°	′	
Watabeag	80	33·0	48	34·1	−443
Ramore		19·3		26·3	228
Timagami	79	47·0	47	03·9	292
Jct. Routes 11 and 64		49·9	46	43·1	394
Holdridge Creek		54·1		40·8	433
Field	80	01·6		31·5	325
Sturgeon Falls	79	55·7		22·0	374

TABLE 1 (*e*)—COCHRANE-MOOSONEE TRAVERSE

This traverse was observed in 1947. Most stations were repeated on the return trip to Cochrane.

Station	Longitude		Latitude		Bouguer Anomaly 10^{-4} cm/sec^2
	°	′	°	′	
Cochrane	81	00·7	49	03·7	−517
Genier		01·4		10·5	467
Clute		00·4		11·5	451
Blount		01·8		15·9	379
Gardiner		02·0		18·7	403
Workman		03·7		22·9	393
Wurtele		05·8		25·9	364
Maher		10·9		28·0	343
McInnis		19·0		32·2	266
Island Falls		21·3		32·7	246
Island Falls North		21·4		32·8	236
Brownrigg		31·8		41·7	097
Fraserdale		37·2		51·0	+015
Fraserdale		37·2		51·1	+015
Coral Rapids		40·2	50	12·7	−089
Coral Rapids North		40·3		12·8	083
Onakawana		25·7		36·0	253
Onakawana North		25·5		36·4	148
Moose River		17·8		48·5	067
Moose River North		17·8		48·8	069
Renison		08·0		57·7	151
Galeton	80	55·0	51	07·9	170
Moosonee		39·0		16·5	115

GEOLOGICAL SIGNIFICANCE OF THE MAJOR STRUCTURES DEVELOPED

The procedure so far has been merely to find structures of such size and shape as to produce anomalies approximating the observed ones, without reference to the geology of the Shield. It is evident, however, that there is a relationship between these structures and the geological history of the region. In order to follow the correspondence between the gravity anomalies and the regional geology of northeastern Ontario, reference may conveniently be made to the accompanying anomaly map and to the Lake Huron Sheet (map 155A) of the Geological Survey of Canada.

The major geological features of the area under consideration follow two distinct lines of orientation. On the one hand, certain structures, such as the great fault zone which extends from south of Kirkland Lake into Quebec, strike generally east-west, while other large structures strike northeast-southwest. This would suggest that two separate periods of tectonic activity were responsible for the major structures of the region. The exact age relationship between the two periods remains a major problem of Canadian geology, but one possibility has been clearly outlined by Gill[4] who states:

"In the Grenville sub-province, although the local structures are quite complex, there appears to be, from the limited data available, a prevailing northeasterly trend. As has already been pointed out, this trend cuts directly across the east-west trend of Keewatin and Timiskaming type rocks along a line extending from the north shore of Lake Huron to Lake Mistassini. These relations strongly suggest that the Grenville sub-province marks a late Precambrian mountain built belt with a trend later followed to the southeast by the Palæozoic mountain systems."

Similar relationships were observed by Norman[5] in the Chibougamau district of Quebec. A complete treatment of this hypothesis, that the northeasterly trending structures truncate older, east-west striking, Keewatin features, has been given by Wilson[6]. Wilson has also quoted age determinations to support this thesis. These are probably not completely reliable, but do suggest an age of 2200 million years for a Keewatin rock of southeastern Manitoba (unfortunately no good determinations of the Keewatin in Ontario are yet available) and an age between 800 and 1100 million years for Grenville rocks of Ontario.[7]

It seems reasonable to suppose, therefore, that the Keewatin and Timiskaming rocks of northeastern Ontario were deformed during early Precambrian times by forces which acted along a north-south axis. Judging from the magnitude of the thrusts involved, for example, the Larder Lake-Cadillac break, it is quite possible that mountains of considerable size were developed along east-west lines at this time. Later in Precambrian times, if the hypothesis outlined above be true, the axis of the dominant crustal forces must have changed in direction, for reasons not clearly understood. The new direction of the thrust

---

[4] Gill, J. E.,—The Canadian Precambrian Shield,—Structural Geology of Canadian Ore Deposits, Jubilee Volume, Can. Inst. Min. and Met., pp. 20-48, 1948.

[5] Norman, G. W. H.,—The Northeast Trend of Late Precambrian Tectonic Features in the Chibougamau District, Quebec,—Trans. Roy. Soc. Can., 3rd Series, Vol. 30, Sec. 4, pp. 119-128, 1936.

[6] Wilson, J. T.,—Some Aspects of Geophysics in Canada with Special Reference to Structural Research in the Canadian Shield. Part 2. An Approach to the Structure of the Canadian Shield,—Trans. Am. Geophys. Union, Vol. 29, No. 5, pp. 691-726, 1948.

[7] Wilson, J. T.,—Some Major Structures of the Canadian Shield,—Trans. Can. Inst. Min. and Met., Vol. 52, pp. 231-242, 1949. Appears in The Can. Min. and Met. Bull., Vol. 42, No. 450, pp. 543-554, 1949.

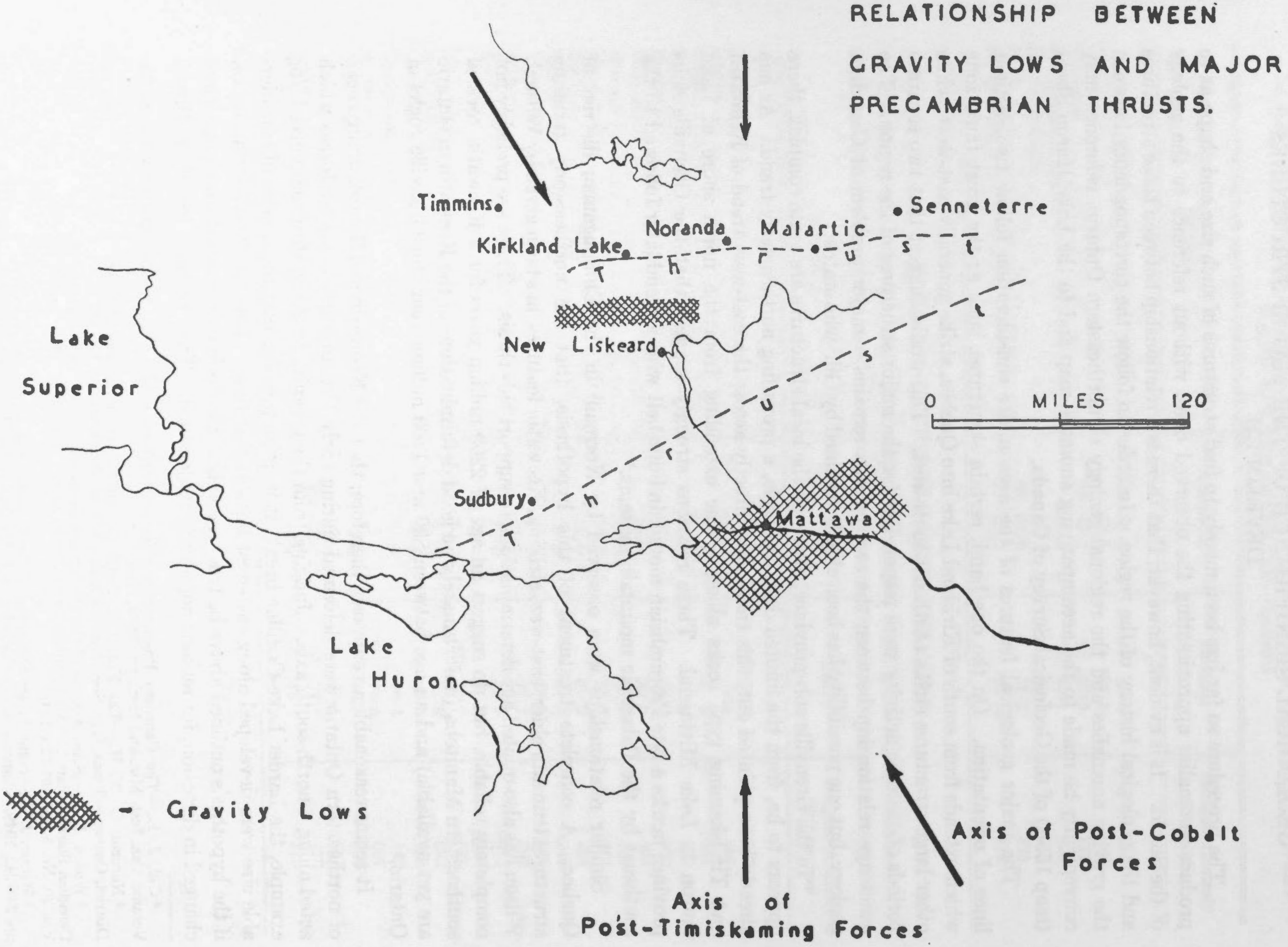


FIG. 18. Sketch showing relationship between gravity lows and major Precambrian thrusts.

forces was approximately northwest, and these forces are believed to have produced the northeasterly trending range of mountains along the border of the Grenville sub-province, as described by Gill. The foreland to the northwest of this range apparently remained a low basin, and in this basin were deposited (partly through the agent of glaciation) the products of erosion from the mountains, in the form of the Cobalt sediments. Further action of the forces after Cobalt time may well have produced the deformation in the Cobalt sediments, which has been clearly shown by Collins[8]. Later work suggests the presence of a great thrust fault bounding the Cobalt province on the southeast. This fault was recognized in the Sudbury district by Cooke[9] and has been shown as extending a long distance into Quebec in a recent publication of the Geological Survey[10]. Norman[11] has recently suggested that the northeasterly trending faults of the Chibougamau and Mistassini districts of Quebec may form part of a major late Precambrian structure which separates the Timiskaming and Grenville sub-provinces. The straight (apparently transcurrent) fault which cuts the Palæozoic rocks north of Lake Timiskaming would indicate that thrusting along an approximately northwest axis had occurred even after the Silurian period.

To show that a relationship may be expected between the structures developed within the granitic layer and the tectonic processes outlined above, reference may be made to papers by Vening Meinesz [12] and Hess [13]. These papers suggest the relatively new concept of a tectogene, which is primarily a great downbuckle of the earth's crust, (Fig. 19) constituting one stage in the formation of a range of thrust mountains. The complete process may be said to begin with the accumulation of sediments in a geosyncline followed by the application of great tangential, compressive forces, which probably act within the granitic layer. Eventually, this layer must buckle, forming a downfold as the underlying basaltic material is pushed aside. If the forces continue to act with sufficient magnitude, the fold will become isoclinal (as shown), and may extend downwards "40 to 60 km." (Hess), that is, to the base of the basaltic layer, or beyond. The overlying sediments, during this stage, become very highly folded, and if caught in the centre of the granitic fold, may be thrust upwards. Examples of tectogenes in this stage are believed to exist in the world today, among the island arcs of the West Indies and the Asiatic margin of the Pacific. Characteristics of these regions include ocean deeps (evidence of the downfolding), folded sediments, volcanics and marked negative Bouguer anomalies. For example, over the West Indies narrow strips with negative anomalies of about 150 milligals are observed, representing almost as great a negative anomaly as found in the Canadian Rockies. Following the development of the tectogene, buoyant forces acting on the granitic root cause the entire mass to rise, so that eventually the deformed sediments above the fold become mountains of considerable size. Erosion then takes place, and the

---

[8] Collins, W. H., —North Shore of Lake Huron,—Geological Survey of Canada, Memoir 143, 1925. Especially pp. 98-107, and figures 7 and 8.

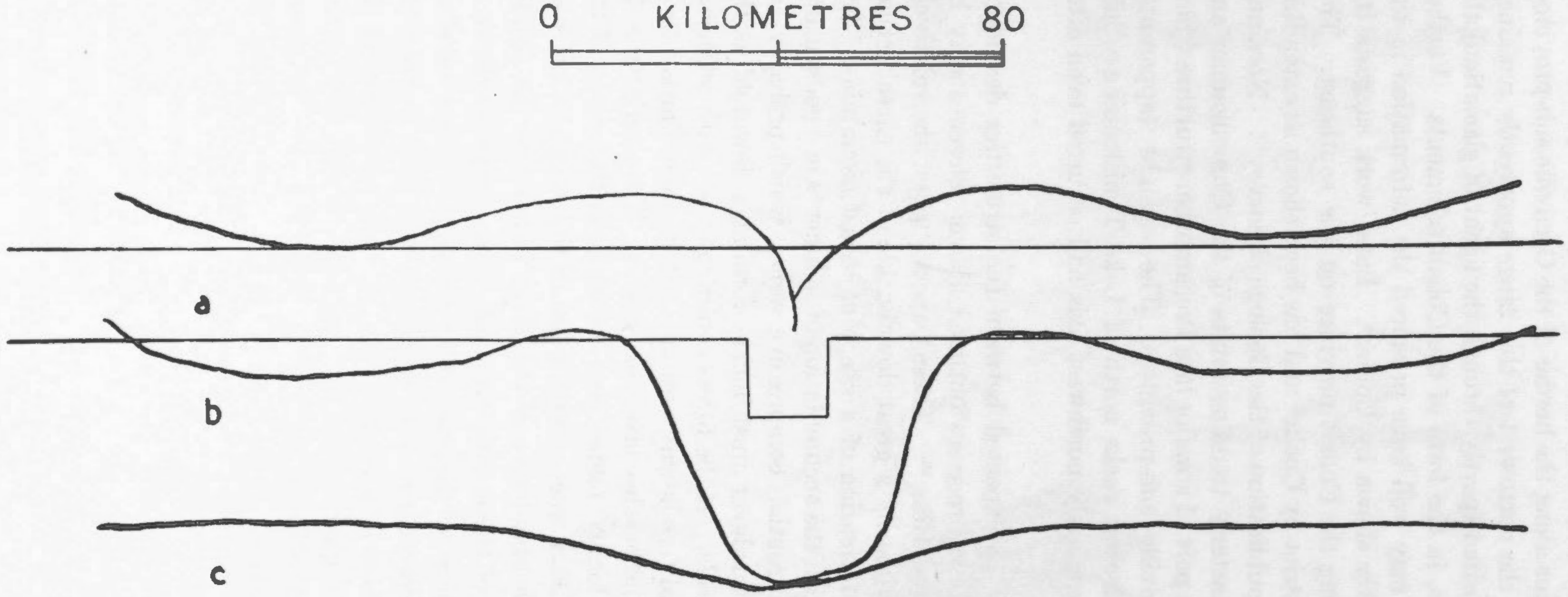
[9] Cooke, H. C.,—Problems of Sudbury Geology,—Geological Survey of Canada, Bulletin No. 3, 1946.

[10] Geology and Economic Minerals of Canada,—Third Edition, 1947.

[11] Norman, G. W. H.,—Major Faults, Abitibi Region,—Structural Geology of Canadian Ore Deposits, Jubilee Volume, Can. Inst. Min. and Met., pp. 822-839, 1948.

[12] Vening Meinesz, J. H. F. Umgrove, and Ph.H, Kuenen,—Gravity Expeditions at Sea 1923-32., Vol. II, Publications of the Netherlands Geodetic Commission, Chapter V.

[13] Hess, H. H.,—Gravity Anomalies and Island Arc Structure with Particular Reference to the West Indies. Proc. Am. Phil. Soc., Vol. 79, No. 1, 1938.



THE TECTOGENE

(as suggested by H. H. HESS for the West Indies.)

(a) Granitic Layer
(b) "Intermediate" (Basaltic) Layer
(c) Ultrabasic Layer

In light lines are shown the average thickness for the Granitic layer of Ontario and the remnantal root suggested for the Matachewan — Guerin Low.

FIG. 19. The tectogene as suggested by Hess for the West Indies.

mountains are reduced. But does the granitic root gradually disappear as the topography is levelled? The anomalies observed in the Canadian Shield would indicate that the roots outlive the mountains.

The major anomalies considered in the previous section exhibited two outstanding strike directions, east-west and northeast-southwest. It appears reasonable to consider the former structures (east-west striking) as dating from early Precambrian (post-Timiskaming) time, and the latter from Huronian time. The most prominent anomaly of the first type is the Matachewan-Guerin low, which extends for at least seventy miles across the country immediately south of the Kirkland Lake-Malartic belt of highly folded and faulted Timiskaming sediments. These sediments may reasonably be identified as the remnants of deeply eroded mountains, formed by the north-south thrust. It is now suggested that the thickened granitic layer, as developed to explain the gravity low, represents the remnant of the root formed during the tectogene stage of the mountain building. In the diagram of the West Indies tectogene (Fig. 19), the Matachewan-Guerin structure has been added, in light lines, for comparison. The latter structure, as expected, could be merely a relatively small core of the original root, since, of course, the root decreases through the very act of rising under buoyant forces. Further outflow of granite is to be expected during the long history of the mountains, but the conclusion to be emphasized here is that at least a remnant of the original root may have persisted since early Precambrian times.

The surface rocks along the axis of the low are dominantly granite and granite gneiss, while areas of Keewatin lavas appear both south and (to a greater extent) north of the low. The Timiskaming sediments are also located to the north of the trough, and their trend appears to be related to minor sinuosities in the gravity contours. For example, Fig. 20 shows the gravity results along the sedimentary belt from Swastika to Rouyn, with the anomaly contour at -40 milligals plotted. This contour may be taken as indicating the northern limit of the low, and it will be observed that the prominent southward extension of the Timiskaming rock, in the vicinity of Larder Lake, corresponds with a similar southward trend in the contour. Now, if the low does represent the effect of a remnantal root, it seems logical that the highest mountain elevations lay along what is now the axis of the low. During the great erosion, which reduced the mountains to the surrounding level, the folded sediments and volcanics which constituted the mountains were removed, exposing areas of granite. The latter rock may be assumed to have been intruded, as batholiths, during the mountain building process. Thus, the prominent rock along the course of the gravity low today is granite, while the Timiskaming sediments which best escaped erosion were those occupying some favoured position along the northern limit of the range.

Unfortunately, other east-west trending regional anomalies, while definitely suggested, are not yet as well defined as the Matachewan-Guerin low. There is recognized a second belt of Timiskaming rocks, reaching from Destor, Que., (latitude 48° 30′ longitude 79° cf. Lake Huron Sheet G.S. Map 155A) to the Porcupine area of Ontario, which is similarly characterized by thrusting assigned to forces acting along a north-south axis. As shown on the contour map, there is an area of low gravity centring about Porcupine about 8 miles east of Timmins, and at least a suggestion of its eastward continuation across the

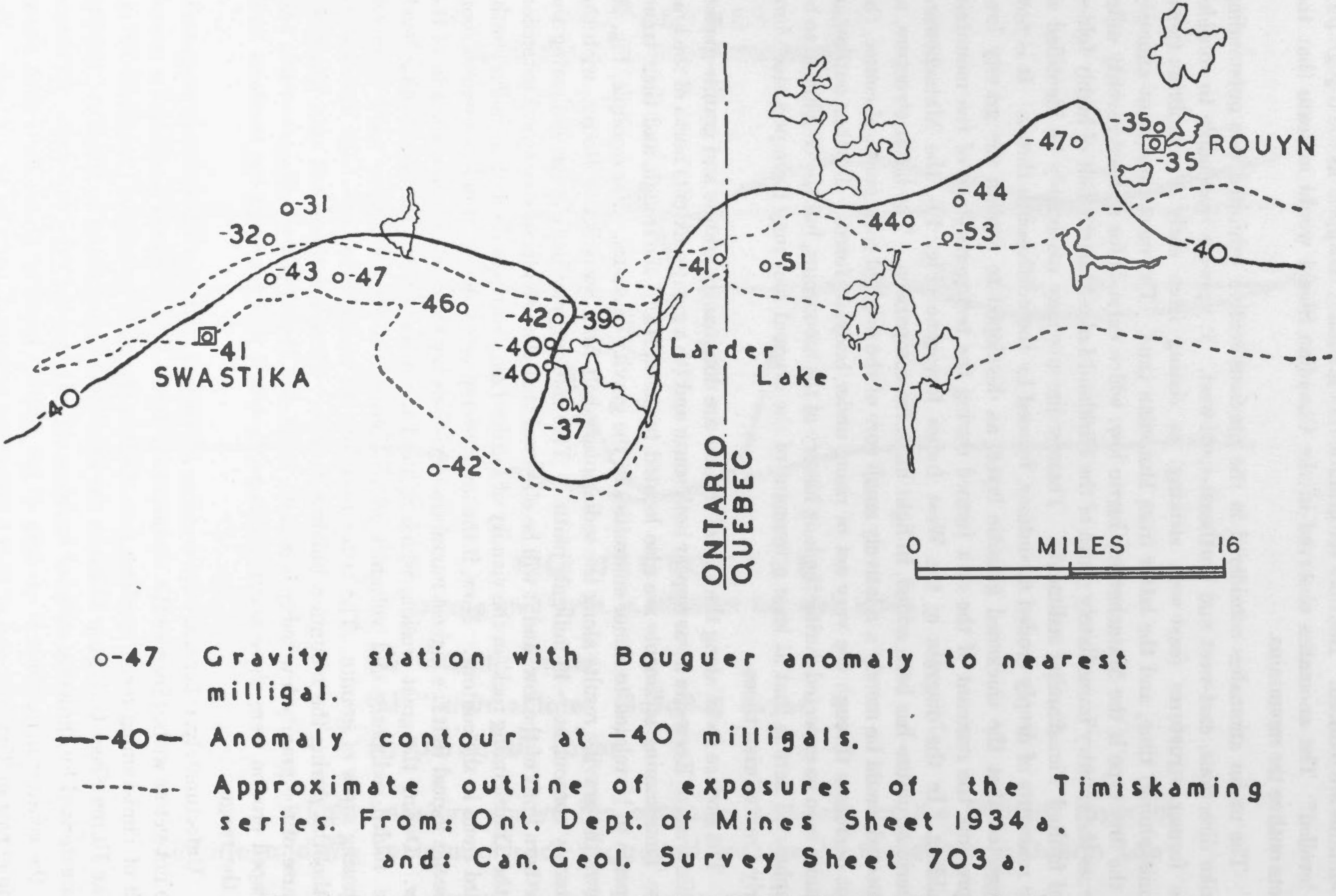


FIG. 20. Showing relation between gravity anomalies and Timiskaming series—Rouyn to Swastika.

traverse on Highway 11. However, the latter low has the characteristics of a surface, rather than a crustal anomaly, and as such is treated later. (It will be suggested that a ridge of granite extending into the otherwise deep Keewatin lavas is the anomalous structure). Further traverses are necessary to show the outlines and trend of the Porcupine low proper, but it may well represent a root structure under the granitic layer which could be related to the thrusting of the region. The second suggested anomaly of this type is the Port Arthur low. As explained previously, this could be an east-west trending feature with its northern limit extending from Ouimet Station to Dyment, and its southern limit as yet undefined. If this can be shown to be true, the root structure suggested by the low could be related to the early Precambrian folding in the volcanic and sedimentary rocks of the Rainy Lake area, as this folding has a dominant east-west trend. This orientation would also place the structure very nearly in line with the Matachewan-Guerin root, possibly indicating that it was the westward extension of the same early Precambrian tectogene.

The second group of the structures, those striking northeast, may now be considered. These, of course, are considered to have resulted from thrusts acting from the southeast during the later Precambrian periods. It was shown that a granitic layer thickening of about 4·5 kilometres could explain the gravity low in the Mattawa area. The location of this low corresponds with the assumed position of the mountains thrust up along the northern limit of the Grenville, and the thickening may, therefore, be the remnant of the roots of these mountains. During the thrusting, as granitic material flowed downward into the root being formed, a thinning of the granitic layer northwest of the root may have occurred. Hence, while the mountains were rising, the area to the northwest may have remained low, or even sank, to form a natural basin in which the Cobalt sediments were deposited. Evidence consistent with such an explanation was shown in the traverse through Sudbury (Fig.6), and also in the Englehart region. Further traverses over the Cobalt basin may well show that the gravity high exists over most of the area covered by the sediments, as would be expected if the basin was formed as suggested. Once again, the dominance of granite, and granite gneiss, along the course of the low may be noted, indicating that the axis of the gravity low represented the line of highest elevation, and hence of greatest erosion. Southeast of the low, gravity increases, suggesting a return to normal thickness of the granitic layer. Thus, along the traverse between North Bay and Ottawa, the southeasterly boundary of the thickened granitic layer appears to be near Chalk River. The latter point also marks approximately the northerly limit of large areas of Grenville sediments, beyond which granite is the dominant rock.

It has been suggested that the region of high gravity observed near Englehart is part of a much larger area under which the granitic layer is thinner than normal (the Cobalt basin). The contour map would suggest an interaction between this high and the Matachewan-Guerin low to the north. That is, the higher contours tend to distort the east-west trending low, causing it to be most narrow just north of Englehart. At the time the Cobalt basin and the mountains to the southwest were forming, the Matachewan-Guerin root was, in all probability, already an ancient structure. Possibly it suffered a certain deformation under the late Precambrian forces.

The gravity observations over the Palæozoic outlier of Lake Timiskaming are interesting. This outlier lies within the area of relatively high gravity, that is, over a supposedly thinner than normal granitic layer. Theories to explain this outlier vary in detail, but there is suggestion of a downwarping of the crust, which aided in the preservation of the Palæozoic rocks. The following paragraph is quoted from Hume.[14]

"The evidence seems to show that the Palæozoic rocks of the Timiskaming area owe their existence chiefly to a depression formed by warping of the Canadian Shield subsequent to their deposition. Afterwards these strata were further depressed and sheltered from erosive agents by a great fault which extends northwestward along the straight western shore of Lake Timiskaming and perhaps also by a small fault extending through Cobalt northeastwards towards Rivière des Quinze."

It is reasonable to suggest that the downwarping of the Shield occurred partly as a result of the thinned granitic layer, which would make the crust less competent to support the extra load of the sediments.

Still another northeast trending structure is the Kapuskasing-Fraserdale high, also attributed to a thinning of the granitic layer. As this trend is believed to be characteristic of the later Precambrian structures, the high may have been the result of the same northwesterly thrusts. The buckling of the granitic layer under the action of these thrusts seems to have taken the form of a thickening under the "Mattawa Mountains", a thinning under the Cobalt basin, a lesser thickening northwest of this, (the contour map shows a moderate low near Cochrane), and the thinning suggested by the Kapuskasing-Fraserdale high. Certain rock types may be noted along the course of this high. A large area of Timiskaming sediments is preserved west and south of Kapuskasing in the vicinity of Michipicoten, within the general limits of the high. Further north the small patches of Cretaceous sediments lie along the same high. Of course, the thinning of the granitic layer, dating from Huronian time, cannot directly explain the presence of the Timiskaming sediments, but it suggests that the region remained one of low elevation during late Precambrian orogenies. This would assist in the preservation of the earlier rocks. The Cretaceous rocks may be found to be downwarped or downfaulted; in either case the thinner than normal granitic layer beneath them could have been an assisting factor.

ISOSTATIC CONSIDERATIONS

One of the objections most likely to be raised to the above interpretations is that the granitic layer is assumed still to reflect the compensation of Precambrian topography, whereas the principle of isostasy would appear to demand the disappearance of roots as the topography is levelled. However, on the basis of recent knowledge of the strength of the crust, this is not necessarily so. It is now believed, for example, that many major topographic features of today are supported by the strength of the crust, rather than by local compensation. Indeed, the criterion of whether a feature is to be compensated or not is no longer its size alone, but rather its mode of formation. Thus, a considerable mountain chain may be formed by the outpouring of lava, and the mountains will be carried by the strength of the crust alone. The Hawaiian islands are believed to be an

---

[14] Hume, G. S.,—Geological Survey of Canada, Memoir 145, p.51.

example of such a feature, being supported by the intermediate layer without local compensation.[15] On the other hand, mountains formed by compressive forces, even if no larger in extent than the volcanic ones mentioned, are found to have roots, largely because the roots were formed first, by the action of the forces. Now, if the intermediate layer can be assumed to carry the entire weight of the Hawaiian islands, it is not too much to assume that the granitic layer of the Canadian Shield can withstand the unbalanced upward forces caused by the remnantal roots suggested. For example, the deepest rock assumed was that developed for the Matachewan-Guerin low. The extra 16 kilometres of granite assumed here (Fig. 8) would exert a buoyant force on the granitic layer above, equivalent to the downward load of a granitic plateau 4,000 feet high, or a basaltic plateau of about 3,600 feet. Elsewhere, the roots assumed are smaller, and the unbalanced buoyant forces correspondingly less. Assuming that the granitic layer proper can withstand these forces, there is really no reason for the roots to disappear completely. During an orogeny, granite may be assumed to flow easily, as it probably becomes plastic under the conditions of increased temperature accompanying the compression. However, during the quiet period of erosion of the mountains, the granitic material in the roots probably becomes sufficiently solidified to assume that at least a core of the original root remains intact for a very long period.

It would appear, therefore, that while the isostatic compensation of the continental mass as a whole is accomplished at some depth much below the granitic layer (possibly partly at the base of the intermediate layer and partly at some still greater depth), the compensation of certain rather major topographic features (especially those produced by great compressive forces) depends on a thickening of the granitic layer formed by these same forces. The normally solid, crystalline nature of the granitic layer would allow these granitic roots to outlive the topographic features they once supported. If this suggestion be true, it would offer a ready explanation for the apparent departures from isostasy observed at various pendulum stations in the area, such as Mattawa and Timiskaming[16].

THE USE OF THE MAGNETOMETER IN OUTLINING THE MAJOR STRUCTURES

Measurements of vertical magnetic intensity were made at gravity stations along certain traverses, for example, between Cochrane and the Manitoba boundary. These observations, reduced to the latitude of Cochrane, are shown in Fig. 22. Quite obviously, there is no close agreement between gravity and magnetic profiles, at least as regards the major gravity anomalies. It would be reasonable to expect some magnetic effect from structures at the base of the granitic layer, if the underlying basalt is more magnetic than the granite (as is usually found in surface types). However, the magnetic anomalies produced by such structures can be shown to be very small, if not undetectable. As an example, the anomaly curve is shown (Fig. 21) for the assumed step-like thickening of the granitic layer near Dyment, Ont., assuming that the susceptibility of the basaltic material is 1000×10^{-6} CGS units, that the susceptibility of the granitic rock is 100×10^{-6} CGS

---

[15] Vening Meinesz, F. A.,—Gravity over the Hawaiian Archipelago and over the Madeira Area; Conclusions about the Earth's Crust,—Proc. Nederl. Aka. wan Wet., Vol. 44, No. 8.

[16] Publications of the Dominion Observatory, Vol. XI, Nos. 3 and 4.

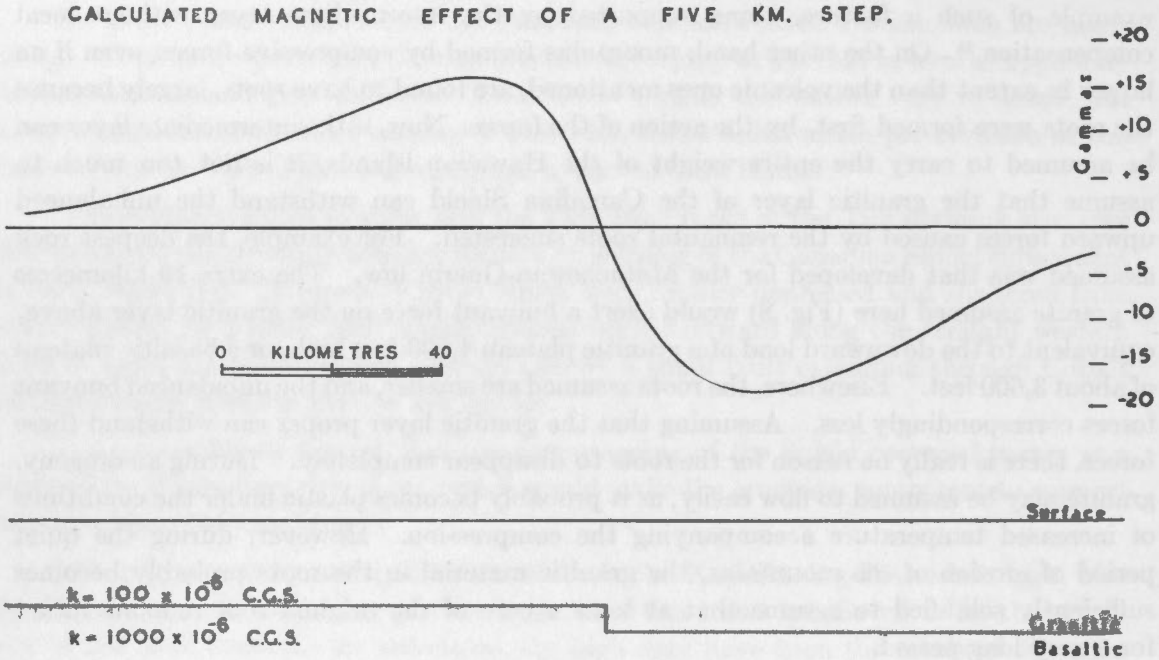


FIG. 21. Calculated magnetic effect of a five kilometre step.

units, and that both layers are uniformly magnetized. This is certainly a liberal estimate for the susceptibility of the lower layer, yet the maximum high over the step is but 16 gammas, and the maximum low off the edge of the step is only 20 gammas. This curve is shown to scale in Fig. 22, and the conclusion is that it is practically negligible in comparison with the other anomalies observed. The observed curve in the same illustration shows that readings between adjacent stations may differ by hundreds of gammas. Apparently, therefore, magnetic rocks near the surface, in the vicinity of the stations, produce effects which completely mask any smaller anomalies that might be caused by structures deep within the crust. The use of combined magnetic and gravity profiles in interpretation would thus appear to be limited to cases where the anomalous structures are not at such great depth, and where the surface formations are relatively non-magnetic. (For example, the Carboniferous Basin of New Brunswick, and the covered Shield area of southwestern Ontario, and Western Canada, have been explored in this manner. But in these cases, the structures sought were at the top of the granitic layer under only a few thousand feet of sediments.) As was suggested before, the airborne magnetometer suggests itself as the most probable means of detecting small regional trends that could be attributed to really major structures in the Shield.

SURFACE EFFECTS

The term "local, or surface effects" as used here refers to any anomaly which can apparently be correlated to known surface formations, on the basis of measured densities. While these anomalies are in general narrower and smaller than the regional effects, they are still of an order of magnitude greater than the anomalies sought in gravimetric prospecting. It should be borne in mind that no anomaly of the latter type is treated in the present discussion.

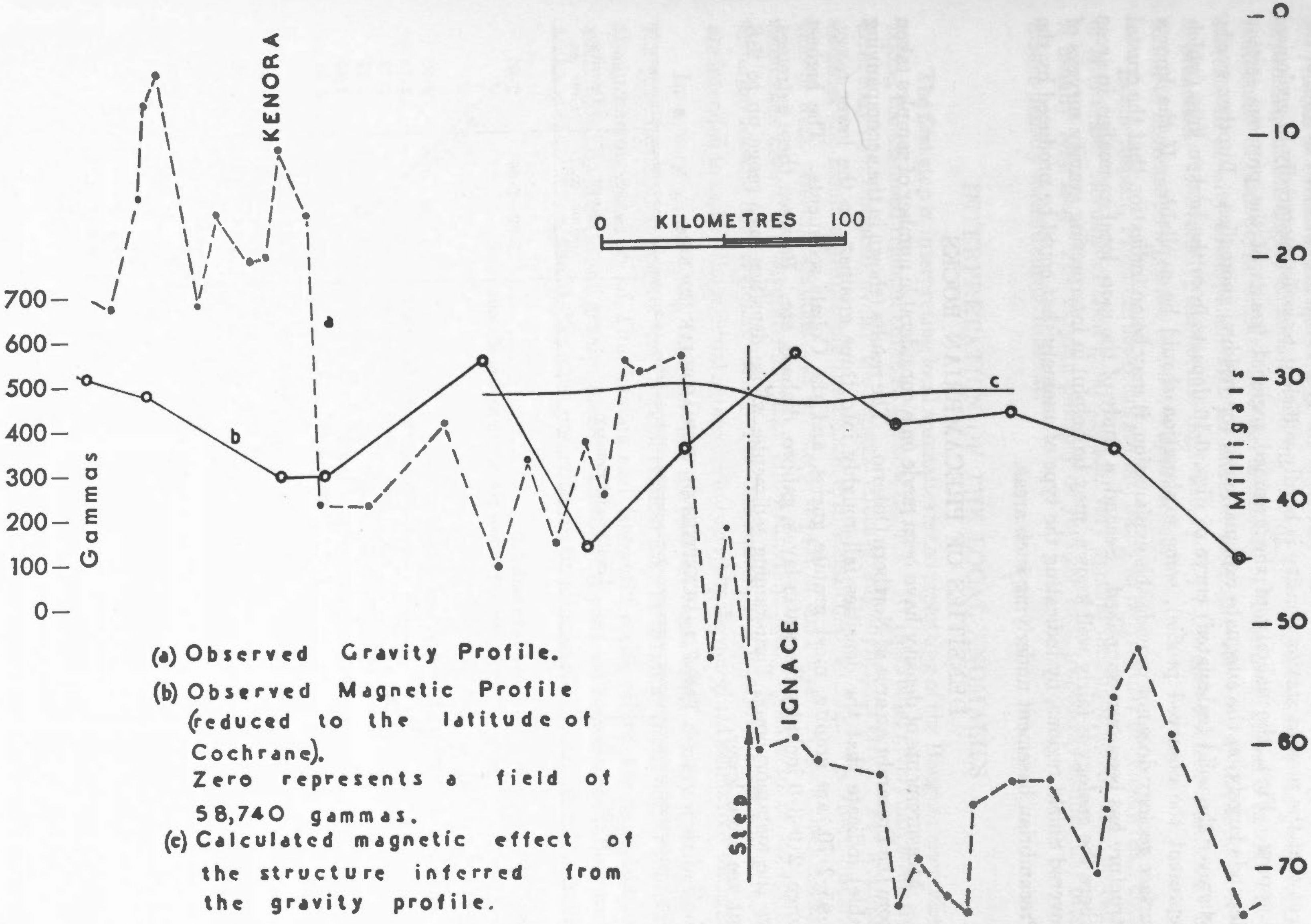


FIG. 22. Gravity and magnetic profiles—Cochrane-Kenora.

The consideration of these surface effects is important for two reasons, in spite of the fact that the present station density is hardly sufficient to assist materially in geological mapping. First, the validity of the assumed regional trends of the previous section depends largely on the adequate explanation of the residual anomalies. In other words, wherever the solid (calculated) curve of Figs. 6-16 departs from the broken lines (which represent the observed profile), some explanation should be available. If the known surface geology does not provide this explanation, it may be an indication that the crustal structure has been over-simplified. Second, a study of the more local anomalies, in areas where the geology is fairly well known, may be helpful in interpreting gravity surveys of covered Shield regions, by indicating the type of anomaly that could be produced by the Precambrian basement underlying such areas.

DENSITIES OF PRECAMBRIAN ROCKS

Measurements of density have been made on a considerable number of samples taken from the Precambrian area of Northern Ontario. The results (shown in the accompanying table) indicate that the densities fall roughly into three groups. In the lower range, 2·65–2·70, are granite, most granite gneiss, and the Cobalt sediments. The highest range, 2·9–3·0 includes Keewatin lavas, gabbro, diabase, etc. Between these extremes, are the metamorphosed Timiskaming sediments, whose densities may range up to 2·8, but are often lower.

TABLE 2—DENSITIES OF PRECAMBRIAN ROCKS

Rock	Locality and Remarks	Density Range Gms. cc.	Mean Density Gms. cc.
Granite	Round Lake batholith Samples taken at various points over an area of about 50 sq. miles.	2·62—2·66	2·65
Granite-Gneiss	Markstay, Ont.		2·70
	Samples taken between Markstay and the fault zone.		2·72
	A visible increase in biotite content of the specimens		2·74
			2·77
			2·84
	Wanapitei—very large proportion of biotite		3·04
Mississagi Quartzite	Crerar, Ont.	2·65—2·67	2·66
	Coniston, Ont.	2·68—2·70	2·69
Cobalt Conglomerate	Near Sesekinika Lake, Ont	2·77—2·80	2·79
Timiskaming Greywacke	Cadillac Area, Quebec	2·79—2·84	2·82
	Timmins Area, Ont	2·84—2·88	2·87
Keewatin "Greenstone"	Englehart District	3·00—3·08	3·03

Rocks of Precambrian age of a given type may vary in density from place to place, depending on the degree of metamorphism. Along the southern side of the great thrust fault south of Sudbury, a marked increase in density of the granite gneiss is noted. This increase in density corresponds with an increase in biotite content, as the fault zone is approached. Conversely, the normal high density of a basic rock such as basalt may be found to decrease as a granite contact is approached.

In one respect, Precambrian rocks are less likely to be irregular in density than those of later eras. Because of their great age and very general metamorphism, their porosity is usually very low. The varying porosity of younger rock (especially sediments) often makes density measurement difficult.

INTERPRETATION OF THE LOCAL ANOMALIES

The first step in interpreting local anomalies is the replotting of the Bouguer anomalies, taking the assumed regional curve as the new datum. At this stage, a very large relative error may be introduced, even if the regional effect is only slightly in error. For example, consider the result of displacing the assumed regional curve in Fig. 15 a short distance east or west. Certain stations near the steepest part of the curve will have their residual anomalies altered by several milligals. Unfortunately there appears to be no certain criterion for the best regional curve. For this reason, the interpretations which follow are intended to satisfy the residual anomalies only within the margin of about four milligals.

In a very general way (and for the purpose of considering density distributions) the pre-Huronian geology of the Canadian Shield may be taken as consisting of comparatively narrow synclines of Timiskaming and Keewatin rocks, which are underlain and surrounded by granite and granite gneiss. The density contrast between the former rocks and the granite is about 0·25 grams per cubic centimetre, so that a considerable gravity

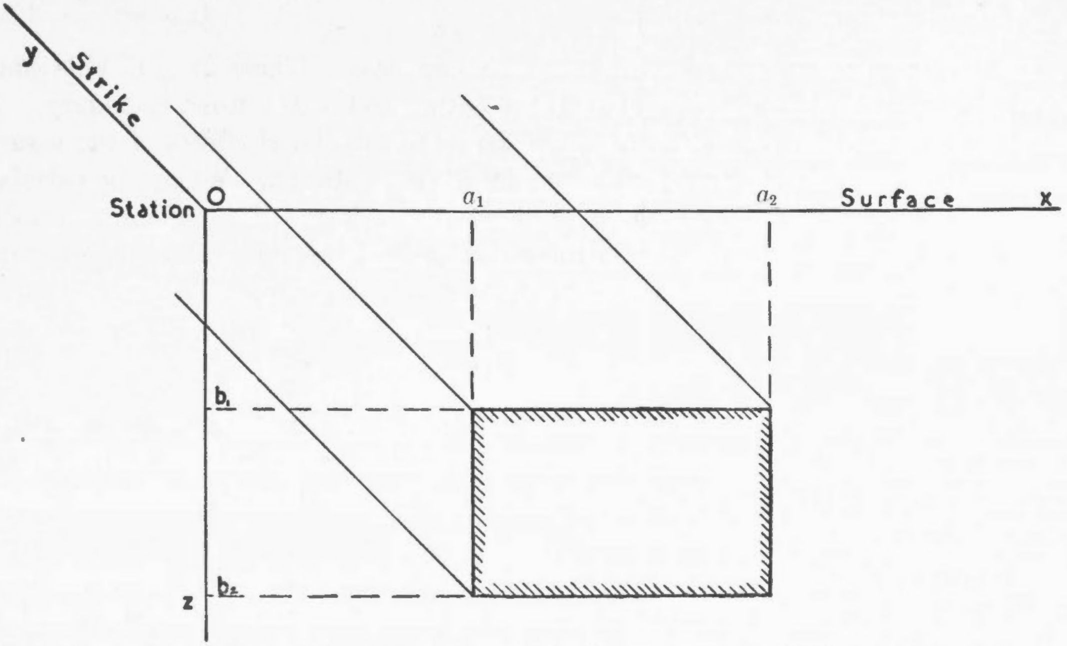


FIG. 23. Illustrating symbols used in the formula for the attraction of an infinite rectangular body.

anomaly may be expected over these synclines. Also, since the synclines lie at the surface, or at the most under a relatively thin layer of drift or sediments, a steep-sided anomaly curve may be predicted, with the edges of the denser rocks fairly accurately demarcated by the inflection points of the curve. It will be shown that along most of the traverses over the Canadian Shield of Ontario just this form of profile is met. In the case of a surface belt of Keewatin rocks (greenstone) of which the edges have been located by mapping, there is really only one unknown: the depth to the base of the Keewatin. Hence, if a good gravity profile is obtained over the belt, it should be possible to make a fair estimate of this depth. This has been attempted in the interpretations which follow. Presumably, such estimates may have some commercial application by giving an indication of the lower limit of ore zones in the greenstone. The other use that has been made of the profiles is the tracing of granite-greenstone contacts under drift, under the Cobalt sediments (near Ville Marie) and under the Palæozoic outlier of Lake Timiskaming (near Englehart).

With a fairly close spacing of stations an estimate may be made of the dip of contacts, and thus of the cross-sectional form of greenstone belts traversed. At present, however, the stations are barely numerous enough to allow such close interpretation, and the belts are treated as rectangles with vertical edges. The fact that curves calculated on this assumption satisfy the observed anomalies as closely as they do suggests that most of the Keewatin areas have steeply dipping edges.

The formula used for the attraction of a two-dimensional (i.e. infinitely long) rectangular body is a useful one. It is:

$$\Delta g = 2G\rho\left\{b_2\left(\tan^{-1}\frac{a_2}{b_2}-\tan^{-1}\frac{a_1}{b_2}\right)-b_1\left(\tan^{-1}\frac{a_2}{b_1}-\tan^{-1}\frac{a_1}{b_1}\right)+\frac{a_2}{2}\log_e\left(\frac{a_2^2+b_2^2}{a_2^2+b_1^2}\right)-\frac{a_1}{2}\log_e\left(\frac{a_1^2+b_2^2}{a_1^2+b_1^2}\right)\right\}$$

where the symbols are explained in the accompanying diagram (Fig. 23). Obviously, the formula can be much simplified for bodies at the surface ($b_1=0$), and for stations over the mid-point or edge-points of a body.

Local anomalies are considered along three traverses. These are (*a*) Ville Marie, (*b*) New Liskeard-Cochrane, and (*c*) from Port Arthur to the Manitoba Boundary. The results are illustrated in Figs. 24-27, which show the calculated effects of the assumed structures, together with the residual anomalies for each station. Where the calculated effects of bodies overlap, the resultant is shown by a dotted line. Known geological contacts are shown by solid arrows on the structure sections, while those inferred from gravity data alone are indicated by broken arrows.

(*a*) VILLE MARIE TRAVERSE

In Fig. 24 are shown both the gravity and magnetic profiles running north from Timiskaming, P.Q., along route 46. The southern section of the traverse is over exposed granite but north of Fabre the surface rocks are largely Cobalt sediments (mostly Lorraine quartzite), often drift covered.

The gravity profile indicates two bands of denser rocks (presumably Keewatin lavas) underlying the Huronian. These are separated by a ridge of granite, evidently the westward extension of a granite batholith which is clearly exposed further east (G.S.C. Map

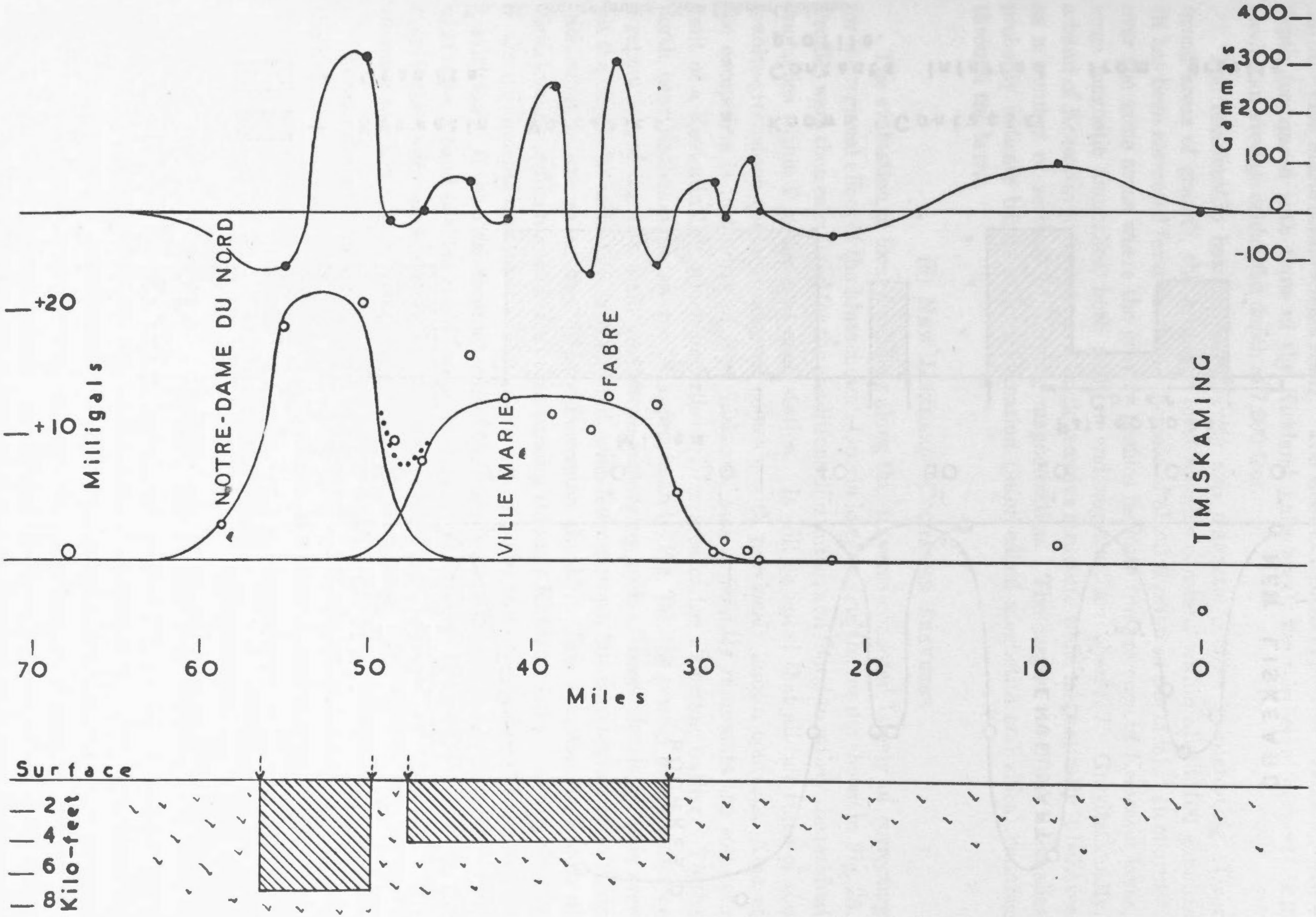


FIG. 24. Gravity profile—Timiskaming-Ville Marie-Notre Dame du Nord.

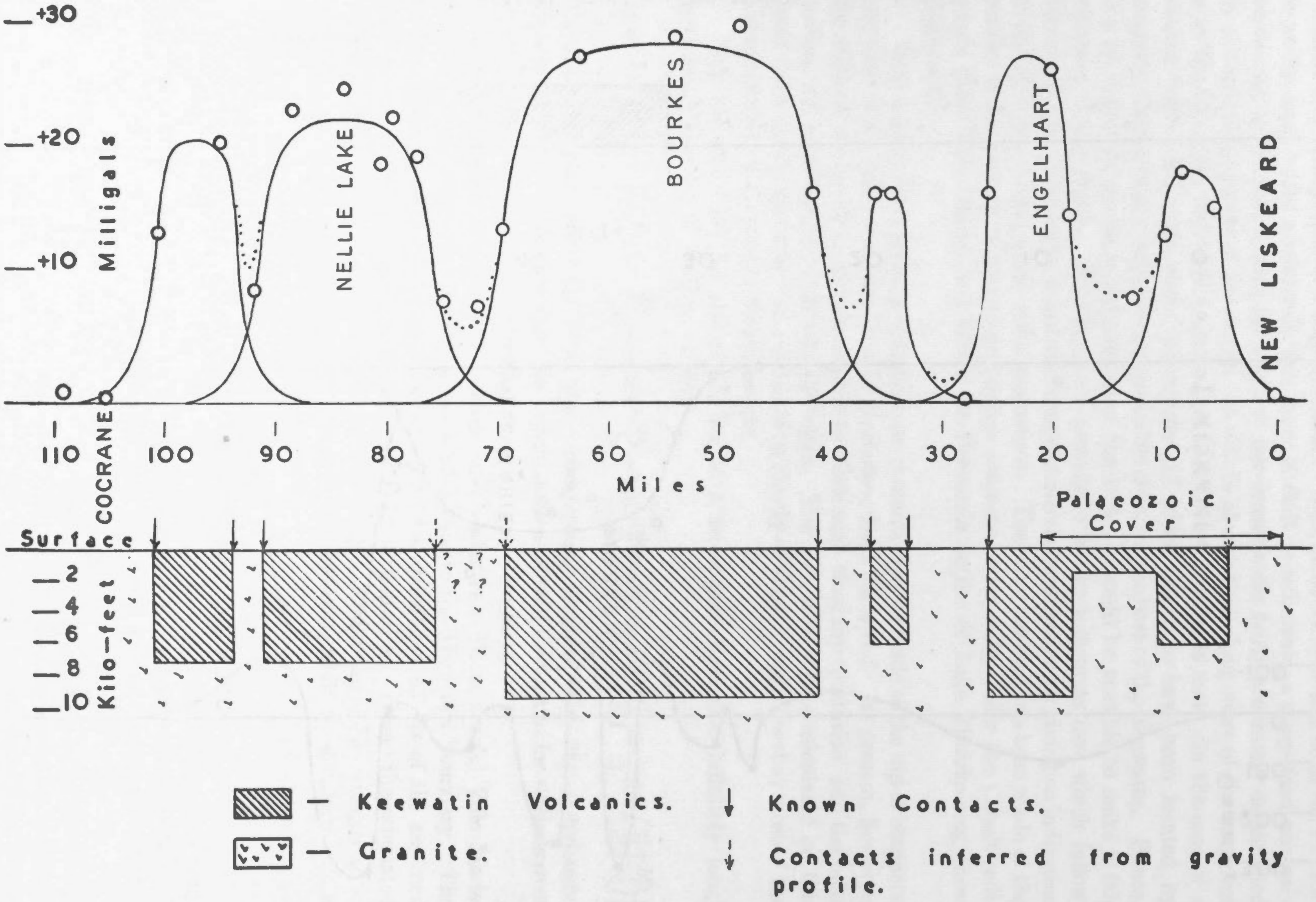


FIG. 25. Gravity profile—New Liskeard-Cochrane.

387 A—Ville Marie Sheet—West Half). The Keewatin rocks appear to reach a moderate depth (compared with those of the Kirkland Lake area), the northerly (deepest) belt having an average calculated depth of 7,000 feet.

The relationship between the gravity and magnetic profiles is interesting. Over broad areas of granite, the magnetic level remains constant within about 100 gammas (it has been corrected for a northerly increase of about 6 gammas per mile). In contrast, over the same areas where the gravity profiles indicate the presence of Keewatin lavas, large magnetic anomalies, both positive and negative, are observed. Gravitationally, a band of Keewatin rocks acts as a single massive structure while magnetically it behaves as a number of sections of varying magnetization. The largest magnetic anomalies probably indicate bands of iron formation (interbedded magnetite and silica) running through the lavas.

(*b*) New Liskeard—Cochrane Traverse

The evaluation of local anomalies along this traverse consisted largely of correcting for the regional effect of the Matachewan-Guerin low, leaving the results shown in Fig. 25. Profiles were then calculated for the conditions illustrated, and found to satisfy the residual anomalies within 2 milligals at each station. It will be noted that all but three of the granite-greenstone contacts adopted coincide with previously known contacts. One of the exceptions is just north of New Liskeard, and apparently represents the southern limit of a Keewatin belt which underlies a large area of the Palæozoic outlier. To the north, near Matheson (at mileage 73, approximately, Fig. 25), the gravity profile indicates a separation of the two main greenstone masses by rock of lesser density. This area (in the clay belt) is heavily drift covered, with few outcrops, but does appear to coincide with what is known as the "Destor-Porcupine Break". This structure is a belt of Timiskaming sediments similar to that passing through Kirkland Lake. As the density of these sediments is rather variable, there appear to be two explanations for the narrow gravity low. If the Timiskaming rocks of the region have a density little greater than that of granite, a band of them could extend to depth, and still give the profile shown. However, if the sediments have a higher density (as is often found) a ridge of granite must be assumed to reach upward toward the Precambrian surface along the course of the break.

The depths indicated for the Keewatin rocks along this traverse (about 9,500 feet for the broadest belt) are interesting, because of the associated gold deposits. This depth is the greatest for any such structure encountered on any of the traverses.

(*c*) Port Arthur—Manitoba Boundary Traverse

In Figs. 26 and 27 are shown the local anomalies and derived geological structure for a traverse from Port Arthur to the Manitoba Boundary (along Highway 17). A number of relatively narrow bands of volcanics, separated by wide areas of granitic rocks, are crossed. Even over the broad stretches of granite variations up to 5 milligals are noticed, as in the Vermilion Bay district. Some of these variations may be due to topography, but the most important factor is probably the varying density of what is

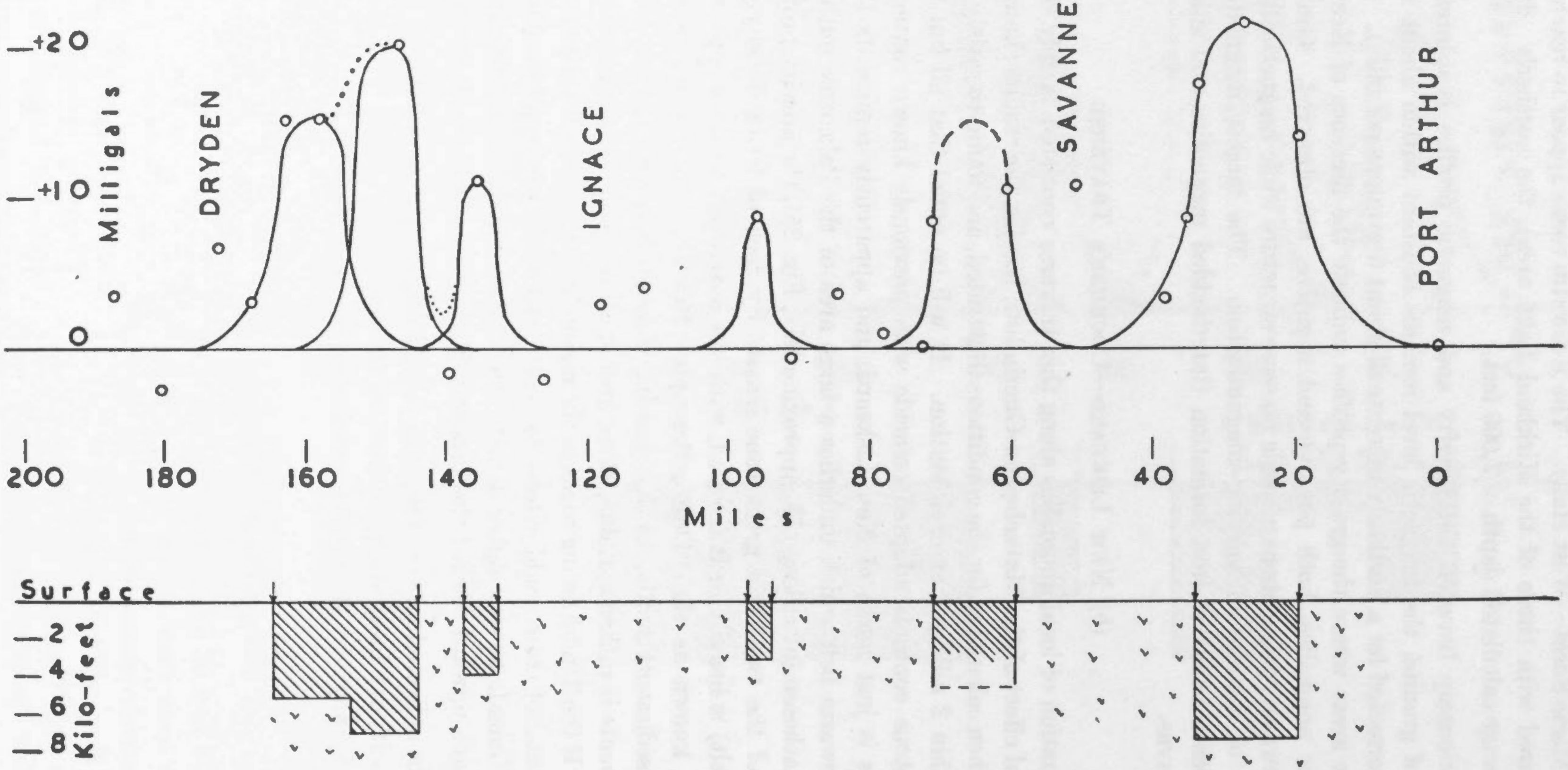


FIG. 26. Local gravity anomalies and derived geological structure—Port Arthur-Dryden.

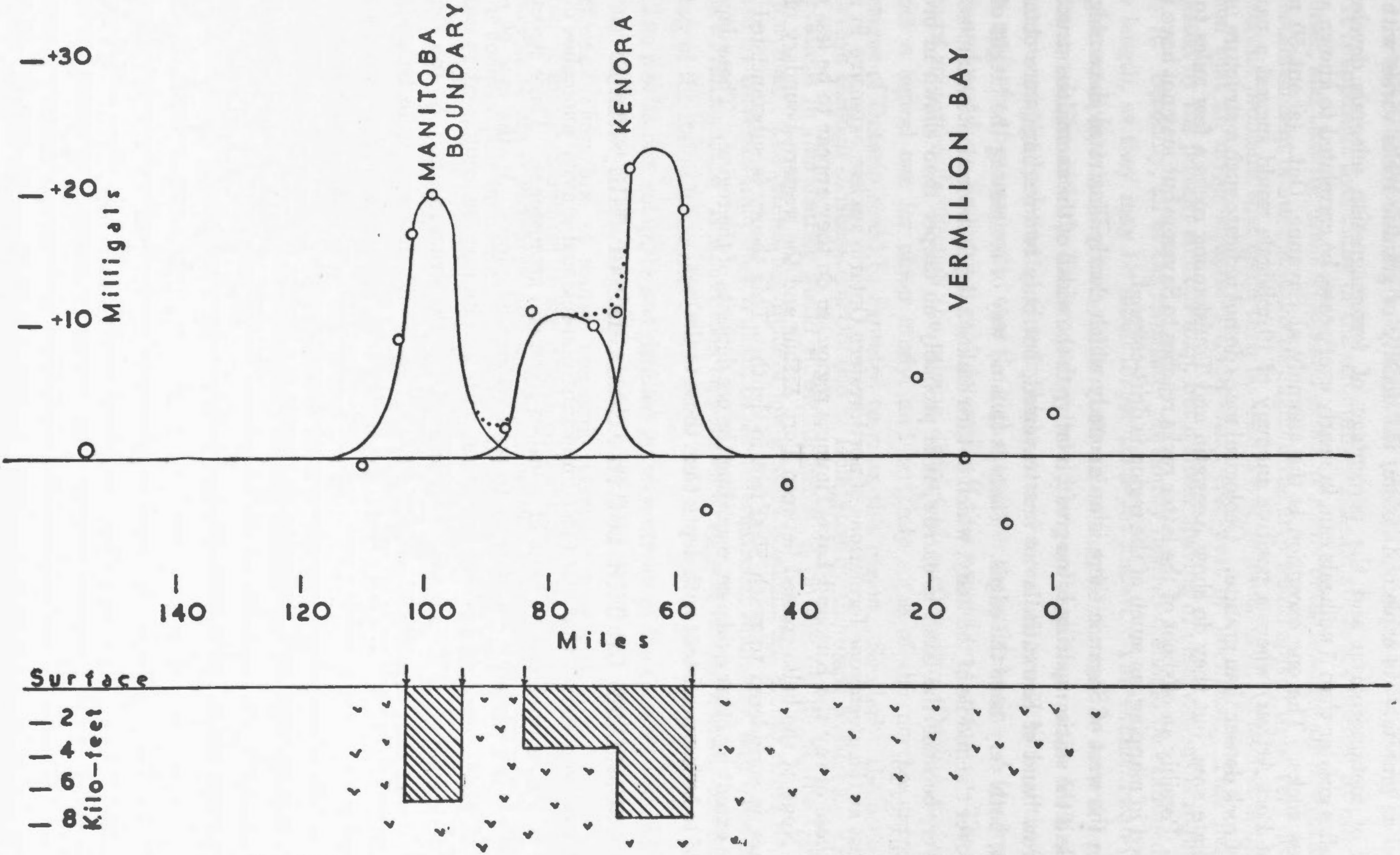


FIG. 27. Local gravity anomalies and derived geological structure—Vermilion Bay-Manitoba boundary.

mapped as granite. As explained before, the density of granitic rocks varies with the degree of metamorphism and the percentage of ferromagnesian minerals developed. Anomalies greater than 5 milligals can, in nearly every case, be correlated to known areas of dense rocks. The one exception is the anomaly at Savanne, Ont., (about 50 miles west of Port Arthur) where a positive anomaly of 10 milligals would suggest a narrow band of rock denser than granite. Geological maps do not indicate such a structure in the immediate area, but they do show Keewatin and Timiskaming rocks a few miles to the south. Possibly an offshoot of the latter rocks reaches to Savanne but may not have been observed in mapping, as much of the region is drift-covered.

To the west of Savanne there is an anomaly which clearly illustrates the ambiguity possible if the station spacing is too great, relative to the width of the anomalous structure. A narrow band of Keewatin lavas was traversed, but only two readings were obtained over it, both very near the edges. There is thus no way of estimating the height of the curve over the middle of the body, which in turn makes a depth determination impossible. However, because the band is narrow, it is probably no deeper than shown in broken lines in Fig. 26.

Just as the greenstone formations of northwestern Ontario are less extensive in area, than those of say the Kirkland Lake-Timmins region, so do they appear to be less deep also. None of the belts crossed between Port Arthur and the western boundary of the province is considered to reach 8000 feet in depth. This theory is substantiated to a certain extent by other evidence, regarding the ore deposits of the region. These deposits are said to be less persistent with depth than those to the east.

SUMMARY OF THE LOCAL ANOMALIES OF THE SHIELD

It has been shown that the most important non-regional gravity anomalies of the Shield are those produced by belts of so-called Keewatin greenstones. These structures have the necessary depth and density to produce marked effects. In the case of other rock types of the Shield the density contrast with granite may be insufficient to cause a measurable anomaly (e.g. the Huronian sediments) or the structures may be too shallow to be located (e.g. diabase sills). Gravity surveys would thus appear to be useful in tracing the limits of these greenstone areas under drift or later formations, with a good degree of reliability. From the profiles, an estimate may be made of the depth to the base of the greenstone.

Since the Precambrian basement underlying the covered Shield areas of southern Ontario and the Prairie Provinces consists of similar rock types to those in the exposed Shield, this same type of anomaly is to be expected in these areas. Across the Prairies, in particular, a number of anomalies of the order of 20 milligals, a few tens of miles broad, were obtained. It is probable that at least some of these represent bands of denser lavas in a generally granitic basement. Of course, since the Precambrian surface lies some thousands of feet beneath the surface of the Prairies, the anomalies do not exhibit the extreme steepness over the edges of the bodies, so characteristic of profiles over the exposed Shield.

SUGGESTIONS FOR FURTHER GRAVITY MEASUREMENTS

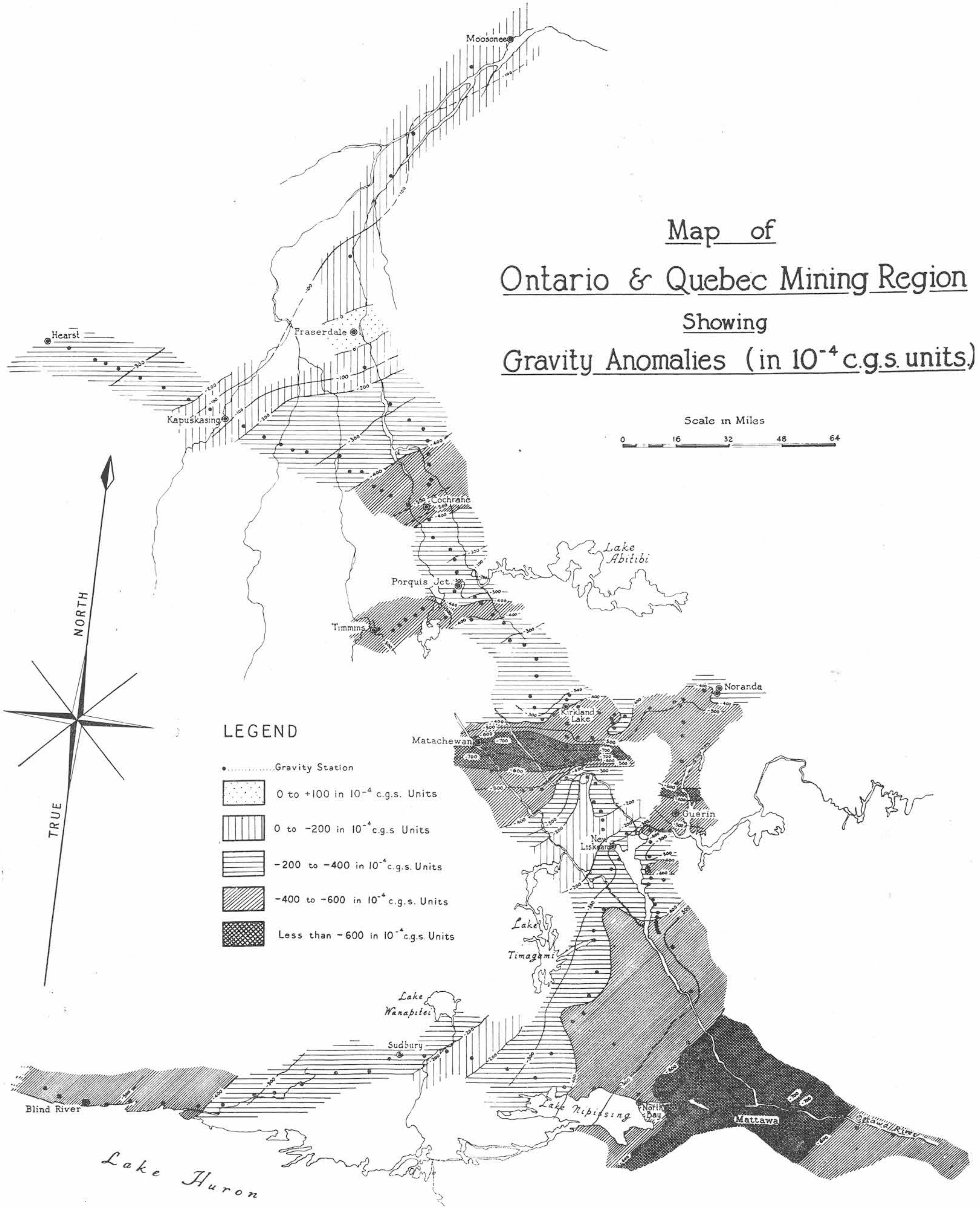
It is apparent that many of the structures discussed above are defined by only a few traverses, and that the exact trends and extent of many of the features are not yet known. The establishment of more stations throughout the area would appear to be very desirable and certain problems that could then be settled will be mentioned. The first is the verification that all major structures trend either east-west or northeast. This has been suggested by the present contour map, but a closer spacing of observations is required to verify it. Secondly, all of the structures previously described should be examined along their length, as they may be much longer than yet known. The Matachewan-Guerin low, for example, is known to be at least 80 miles long, but it may be several hundred. Better correlation with the known geology would be possible if these major features were thus more completely defined. Gravity highs were observed in two sections of the Cobalt basin, and it has been suggested that the high may cover the entire basin. A few traverses north and east from Sudbury should determine if this suggestion is correct. The abundance of motor roads through the mining district of northwestern Quebec makes this district a logical one for closer study, and certainly some of the northeast trending structures of Ontario could be expected to cross this region. Similarly, the completion of surveys through southeastern Ontario is facilitated by the roads available. Gravity observations in this district would throw further light on the nature of the Grenville sub-province. The interesting areas of low gravity around Port Arthur could be better defined by traverses from Fort William to the International Boundary, and from Kenora to Fort Francis, Ont. It would then be possible to suggest further correlations with the geology of the Rainy River area.

The results of a complete and detailed gravity survey of the Canadian Shield would be very important in showing the crustal conditions associated with the great Shield structures. There are, of course, economic advantages to such a survey also. The tracing of major structures in the Shield automatically leads to the outlining of areas favourable to ore occurrences, and any fundamental research on these major structures is thus commercially important. In a more direct way, a complete picture of the regional gravity anomalies of the Shield would be invaluable to the geophysicist exploring for ore bodies with a gravimeter. It has been shown that certain of these regional trends exhibit surprisingly steep gradients, so that a gravimetric survey of even a small area might be confused by them if their regional nature was not realized. With a knowledge of these regional anomalies, the gravity interpreter could apply corrections to his observations, and thereby obtain a more accurate estimation of the smaller, commercially important anomalies.

ACKNOWLEDGMENT

The gravity anomalies discussed in this paper were observed, and largely calculated, by Mr. A. H. Miller and Mr. M. J. S. Innes of the Dominion Observatory, Ottawa. Their kindness in supplying these results made the preceding discussions possible. The author, however, accepts all responsibility for the geological interpretation of the data, and in this respect he wishes to thank Dr. J. Tuzo Wilson, Professor of Geophysics at the University of Toronto, for a great deal of assistance and encouragement in studying the geology of the Canadian Shield.

Map of Ontario & Quebec Mining Region Showing Gravity Anomalies (in 10^{-4} c.g.s. units)



CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
DOMINION OBSERVATORIES

PUBLICATIONS

OF THE

Dominion Observatory

OTTAWA

VOL. XVI No. 2

THE DOMINION OBSERVATORY SEISMIC STATION AT RESOLUTE BAY, NORTHWEST TERRITORIES

BY

Peter C. Bremner

EDMOND CLOUTIER, C.M.G., O.A., D.S.P.
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
OTTAWA, 1952

The Dominion Observatory Seismic Station at Resolute Bay, Northwest Territories

BY

PETER C. BREMNER

ABSTRACT

The Dominion Observatory has installed a seismograph station at Resolute Bay, Cornwallis Island, latitude 74°41'N., longitude 94°54'W. The need for such a station in the Canadian Arctic has been recognized for many years. The establishment of a joint weather station at Resolute Bay offered an opportunity for the installation. A preliminary survey of the terrain indicated that the only outcrop of bedrock was situated at a distance of 1,400 feet from the settlement. At a conference held in Ottawa it was decided that electromagnetic instruments should be used, the detectors to be on the rock outcrop, the recording unit close to the weather station. Field tests carried out at Ottawa throughout a winter season demonstrated the feasibility of this plan.

The station was installed during the summer of 1950. The seismometers were placed on concrete piers and enclosed in a heated, insulated shelter that was subsequently buried with gravel to provide an effective vault. The recording unit was housed in a double-walled, prefabricated building expecially designed for the purpose. Principal source of heat is an oil-fired space heater, but close control is made possible by the additional use of thermostats and electric heaters.

The station is equipped with Sprengnether long-period horizontal seismometers and a Sprengnether short-period vertical instrument. Records are read daily and the data are sent through Ottawa to the United States Coast and Geodetic Survey for use in epicentral determinations.

The paper outlines research investigations undertaken during the first year's operation. The first, a study of near earthquakes, shows that the eastern Arctic islands do not have frequent tremors. The second investigation attempts to associate spurious seismic disturbances with the movement of sea ice by making a careful study of the tide. A third undertaking was the successful operation of a short-period vertical seismometer on a base consisting of steel pipes driven into the frozen ground. It was established that this frozen medium could be used for transmitting seismic radiation to the detector if bedrock was not available. Finally, the occurrence of microseismic storms is discussed in relation to atmospheric disturbances.

INTRODUCTION

Up to the present a major blank space in the world network of seismic stations has been the vast Arctic regions of Canada, where transportation is difficult and where the maintenance of an isolated scientific station is prohibitively expensive. The need for such a station has been recognized by seismologists for many years, both for the study of the seismicity of the Arctic and to make possible more precise epicentral determinations of major earthquakes throughout the world. Several possible sites had been considered in the past, including Aklavik at the mouth of the Mackenzie River and Churchill at Hudson Bay, which is the terminus of a railway line. It was clear, however, from a study of Canadian geography that a location on one of the Arctic islands would be more desirable. By a fortunate chance the establishment of a major meteorological station at Resolute Bay on Cornwallis Island made available many necessary maintenance services on a co-operative basis, and the decision was accordingly made to investigate the possibility of setting up a seismic observatory near the weather station.

PRELIMINARY PREPARATION

RECONNAISSANCE AT RESOLUTE BAY

As a first step in the project the writer travelled to Resolute Bay in the summer of 1948 to study the problems of constructing and servicing a seismic station in the Arctic. Particular attention was given to the availability of rock outcrops, to the types of buildings required to house the instruments, and to transport and maintenance problems likely to be encountered. A rock outcrop was found 1,400 feet south of the weather station. Under ordinary circumstances this would have provided a satisfactory location for the station. However, two difficulties were visualized by station personnel: first, the distance was so long that serious voltage drop would occur in the power line; second, it might be impossible to travel even so short a distance during stormy weather, which sometimes lasts for several days.

A second idea suggested itself. The ground at Resolute Bay is permanently frozen, thawing out only to a depth of about 18 inches during the summer months. This *permafrost* can be used as a satisfactory foundation for heavy equipment, provided that the level of the frozen layer is preserved. For example, the diesel generators which supply power to the station are mounted on timber cribbing extending well down into the frozen ground. This type of construction seemed to offer a possible means of obtaining a stable foundation, at least for the recorder and galvanometers, although it was doubtful that such a foundation would be satisfactory for the seismometers.

It was, therefore, recommended that the seismometers be installed on the rock outcrop, and the recording unit in a separate building close to the weather station.

ADVISORY CONFERENCE AT OTTAWA

A meeting of the Seismic Subcommittee of the Associate Committee on Geophysics of the National Research Council was held in Ottawa on April 29, 1949, to discuss the writer's report and to make specific recommendations for implementing it. In addition to the regular members of the subcommittee, Dr. Beno Gutenberg of the California Institute of Technology, Dr. Frank Press of Columbia University and Dr. E. C. Bullard of the University of Toronto were present and gave valuable assistance. It was agreed that, as suggested in the preliminary report, the seismometers should be placed on the rock outcrop and that a separate building should house the recording unit. No serious difficulties were anticipated with this arrangement although it was agreed that field tests might well be run to reveal any unforeseen complications.

The Committee considered that formation of frost in the hinges of the seismometers might lead to serious reduction in sensitivity unless the seismometer shelter were heated. If this could not be done it was suggested that some means be found to remove all moisture from the air inside the instrument cases.

Although specific instruments were not recommended, it was recognized that they would have to be fairly light because of transportation problems. As the difficulties of the installation were largely unknown it was also recommended that galvanometers of several different periods be made available.

ASSEMBLY AND TESTING OF EQUIPMENT

Following the recommendation of the Associate Committee, Sprengnether seismometers were selected because of their light weight and simplicity of operation. Orders were placed early in the autumn of 1949 and the instruments were available in time for the winter tests.

No outcrop of rock was available for these tests. A substitute was provided by a slab of concrete, 6 feet square and 1 foot deep, laid down for the purpose. The Committee had recommended that the seismometers be housed in air-tight cases. These were constructed of 16-gauge aluminium sheeting and were 20 inches wide, 18 inches high, and 28 inches long. The base of the case was made of ¼-inch steel plate and it was intended that this should be cemented directly to the rock; for purposes of the winter tests it was imbedded in the concrete slab at the time the cement was poured. The top was clamped to the base against a felt gasket, making the case moisture proof. There was a plexiglass window in the top to allow inspection of the seismometer, and an air-tight gland permitted the entry of an electrical cable. After the instruments had been installed in these special cases a simple shelter was used to protect them from the weather.

The recorder and galvanometer were housed in one of the prefabricated huts used in the seismic survey[1], and were set up on steel tables mounted on timbers set into the ground.

To connect the seismometers to the galvanometers a 1,600-foot, two-conductor cable was made up using No. 14 copper stranded wire with $\frac{1}{16}$-inch rubber insulation. The insulated wires were enclosed in a lead sheath, protected with double steel tape armour and covered with jute overall. This cable was strung along the ground, to reproduce, as much as possible, conditions to be expected at Resolute Bay.

Two instruments were used in the tests. The first was a Sprengnether short-period Series DH vertical seismometer, with the coil rewound to 700 ohms, coupled to a Micro Moll galvanometer with a period of 0·3 second. The other was a Sprengnether Series H long-period horizontal, which was tested with three different galvanometers with periods varying from 6 to 22 seconds. Since only a single cable was available at the time of the tests these various combinations were tested one after the other.

Test records were run in temperatures as low as minus 15 degrees Fahrenheit accompanied with strong winds. The short-period instrument operated quite well, but the long-period system produced a confused trace and was subject to the tilting of the concrete pier and temperature fluctuations. When the boom of the long-period seismometer was clamped in its rest position, however, a straight line trace was recorded indicating that there were no spurious currents being induced in the long connecting cables, and, further, that the galvanometers were not subject to temperature drift in the heat-controlled prefabricated building. As a result of the winter test, the concept of remote recording was considered feasible, and it was thought that the solid bedrock and a more sturdy instrument shelter would make it possible to operate the long-period seismometers, at one of the three frequencies provided by the galvanometers available. In the event that the above systems proved unsatisfactory, and also to provide instruments for other studies, two Sprengnether Series DH short-period horizontal seismometers and a Willmore seismometer

---

[1] Hodgson, J. H.: A Seismic Survey in the Canadian Shield, Publications of the Dominion Observatory, in preparation.

were included with the equipment. A Sprengnether three-component microseismic recorder, a chronometer, and a short wave radio receiver completed the instrumentation. Plans for a double-shell prefabricated recording building and for an instrument shelter were drawn up and orders placed for their construction. All this equipment was carefully packed for shipment and was flown to Resolute Bay by the Royal Canadian Air Force, Air Transport Command.

INSTALLATION OF THE STATION

On July 4, 1950, the writer, accompanied by Mr. R. E. Andrews, a summer assistant at the Dominion Observatory, arrived at Resolute Bay to begin construction. By this time most of the snow had melted and the ground could be worked without too much difficulty. Two buildings had to be constructed, first the shelter for the seismometers, and then the hut to contain the recording instruments.

THE SEISMOMETER SHELTER

The seismometer shelter was located on the rock outcrop already mentioned. The outcrop is limestone, badly weathered, and dipping south at an angle of 10 to 15 degrees. The exposed surface is 100 feet long and 75 feet wide, and a small river 10 feet wide and 10 inches deep runs across the centre. In the early spring the river floods for a period of 2 to 3 weeks, at which time the water rises some 12 inches above the normal level. In order that the seismometers would not be under water each spring, an excavation was made 12 feet from the river bank. After removing frozen soil (a mixture of gravel and clay saturated with ice lenses) from a pit 4 feet deep, 10 feet wide, and 18 feet long, a suitable surface of rock was exposed. As the frozen ground about the excavation began to thaw, water collected on the newly exposed surface. A drainage ditch was dug along the dip of the outcrop through the soil barrier between the river and the site. A drain pipe was then made from heavy planks to permit the water to run off the outcrop to the river. Timbers 6 feet in length were bolted together and levelled to make a foundation for the instrument building. There is a large trapdoor in the top of the corridor and a stairway leading down. The shelter was set on the beam foundation and held together with lag screws.

In order to prevent water from being trapped around the beam foundation and causing heaving when it freezes, large stones were piled around the base of the building. These stones were first covered with boards and then with several feet of washed gravel. A box conduit was left to bring in the cables and the shelter was banked with gravel until the roof was level with the ground, the trapdoor previously mentioned providing entrance into the vault. A gentle grade was extended from the roof of the building out to the original ground level.

The gravel fill about this building will serve two purposes. First, it will prevent winds from shaking the shelter and consequently disturbing the seismometers. It will also provide a natural water run-off, for, although the structure is situated at the bottom of a long grade, the gravel bank around the shelter is higher than the surrounding contours. It is hoped that the frozen layer will rise under this new gravel fill making a higher contour and thus forcing the water from melting snow to flow around the vault.

FIGURE 1—Excavation through permafrost to expose bedrock for seismometer shelter.

FIGURE 2—Drain for carrying away the water from the disturbed permafrost. The large stones prevent gravel from blocking the passage of water.

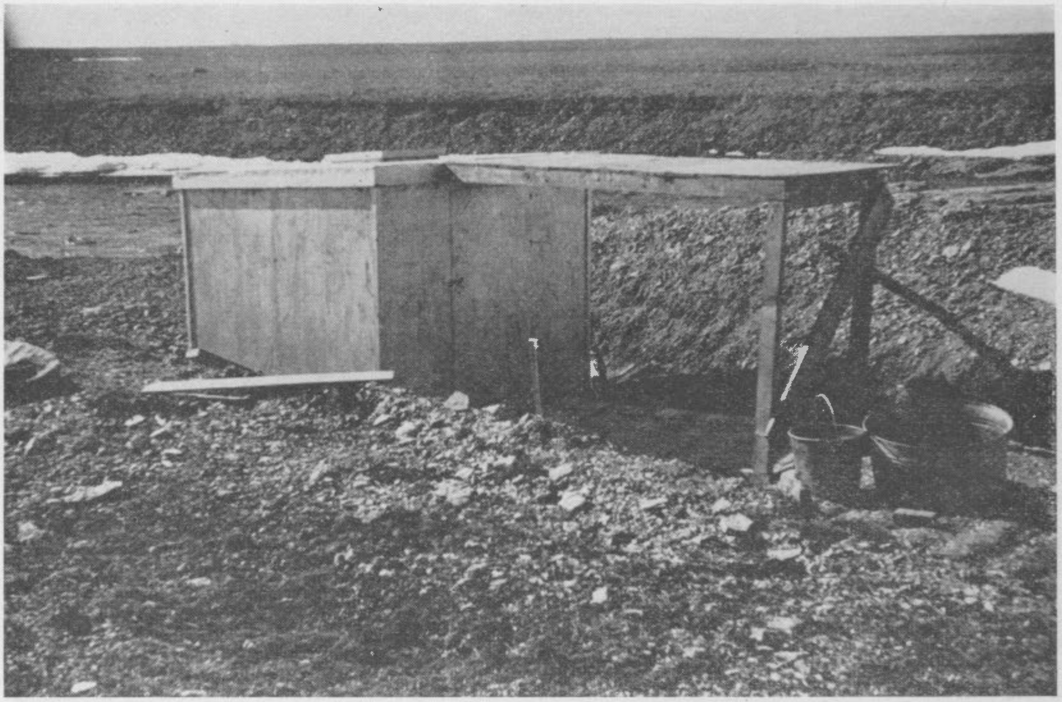


FIGURE 3—The seismometer shelter during construction. Stairs were later constructed in the section at the right to permit entrance to the vault.

FIGURE 4—The seismometer shelter buried with gravel. The trapdoor leads to the stairway mentioned in the caption of FIGURE 3.

The Recorder Hut

Attention was now directed towards the main recording building which was to be located some 175 feet southeast of the electrical power house to minimize the drop in line voltage. The outer shell of this structure was 16 feet square and had a 4-inch wall covered outside with 1-inch weather-proof plywood and backed with 2 inches of rock wool insulation held in place by insulboard. The inner shell was 8 feet square and also had a 4-inch wall made of insulboard lined with rock wool.

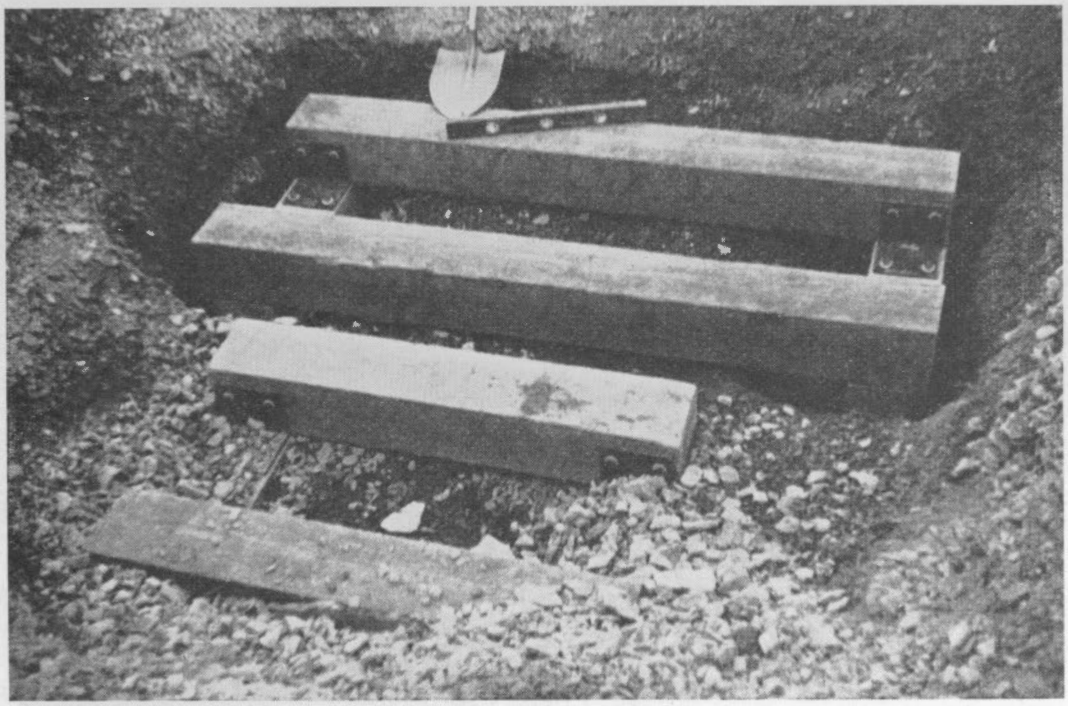


FIGURE 5—Timber cribbing, set in permafrost, to provide foundations for recording tables.

There were two important considerations connected with this part of the project: first, because of strong winds, it was desirable to have rigid foundations, separate from the building itself, for the galvanometer and recorder tables; second, the observatory must be placed on a foundation that would not be affected by frost heaving. These two objectives were achieved by setting the tables on heavy timber cribs set in the frozen ground, and by placing the building on a foundation of washed gravel, 3 feet high, that contained no clay or other materials subject to frost action. The legs of the tables pass through holes built into the floor panels. Insulboard was used to line these holes, which were then filled with rock wool insulation. The beams for the building were levelled, and the structure was assembled without any serious difficulties. A small oil stove was installed in the outer passage to assist the electric heater that controlled the temperature in the inner vault. Finally, a 4-foot gravel bank was shovelled against the outside walls to reduce the effects of wind.

Both buildings being completed, the connecting cables were now laid. The distance from the instrument shelter to the position finally selected for the recording observatory was 1,000 feet. A trench for the cables was made using a road grader with the blade

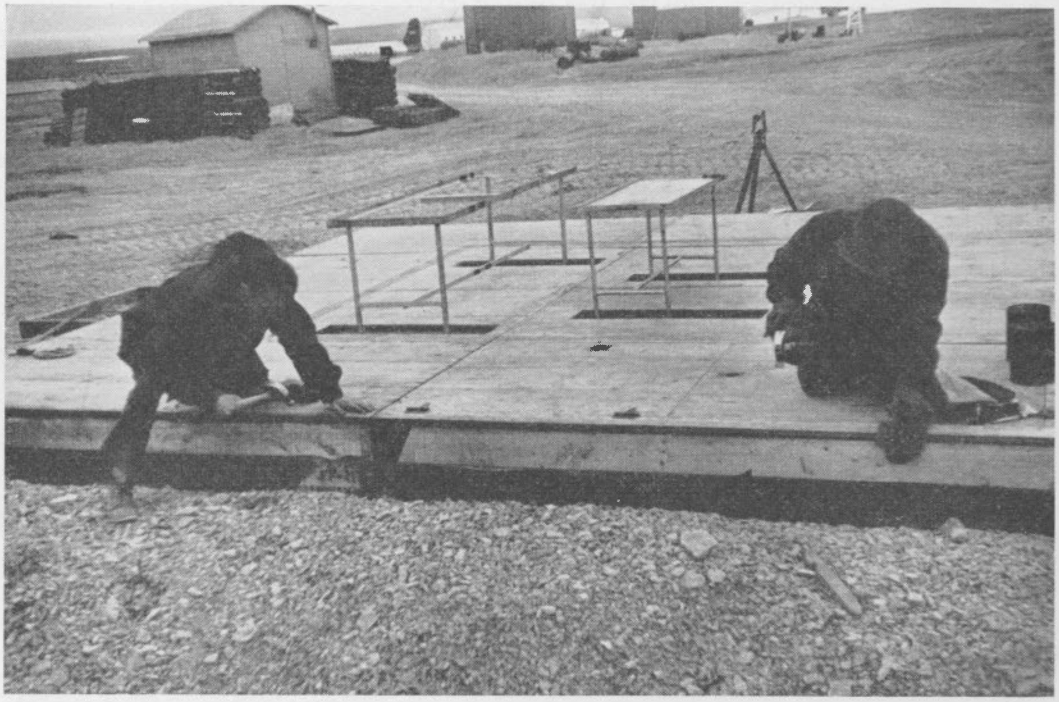


FIGURE 6—The floor of the recording building. Steel tables for the recorder and the galvanometers are shown in place. The legs of these tables are separate from the floor, and rest on the cribbing shown in FIGURE 5.

FIGURE 7—The recorder building under construction. The inside recording room has been completed and the outer protecting building is being erected.

tilted, but in many places further digging had to be done with pick and shovel. The reels of cable, 4 feet in diameter and weighing 1,600 pounds, were mounted two at a time on a sled. Two stands were made, using three sets of timbers, and a steel bar was run through the centres of the reels so that they were free to turn. The sled was pulled by a tractor and the cable laid out along the trench. In all, seven cables were laid, five seismometer connecting cables, one power line made from the ends of the seismometer cables, and one telephone line. The ends of the seismometer lines were spliced into special moisture-proof marine terminal boxes fitted with sealing glands and containing the electrical leads to the seismometers and galvanometers respectively. The trench was refilled and clearly marked with stakes to warn heavy traffic of its presence, and to assist the operator in locating the vault in the dark.

A 220-volt line was buried underground from the power house to the observatory and to the instrument shelter. It was hoped that it would not be necessary to heat the seismometer shelter but it seemed advisable to lay the power cable while the trench was open. Both structures were wired for lights and electrical outlets.

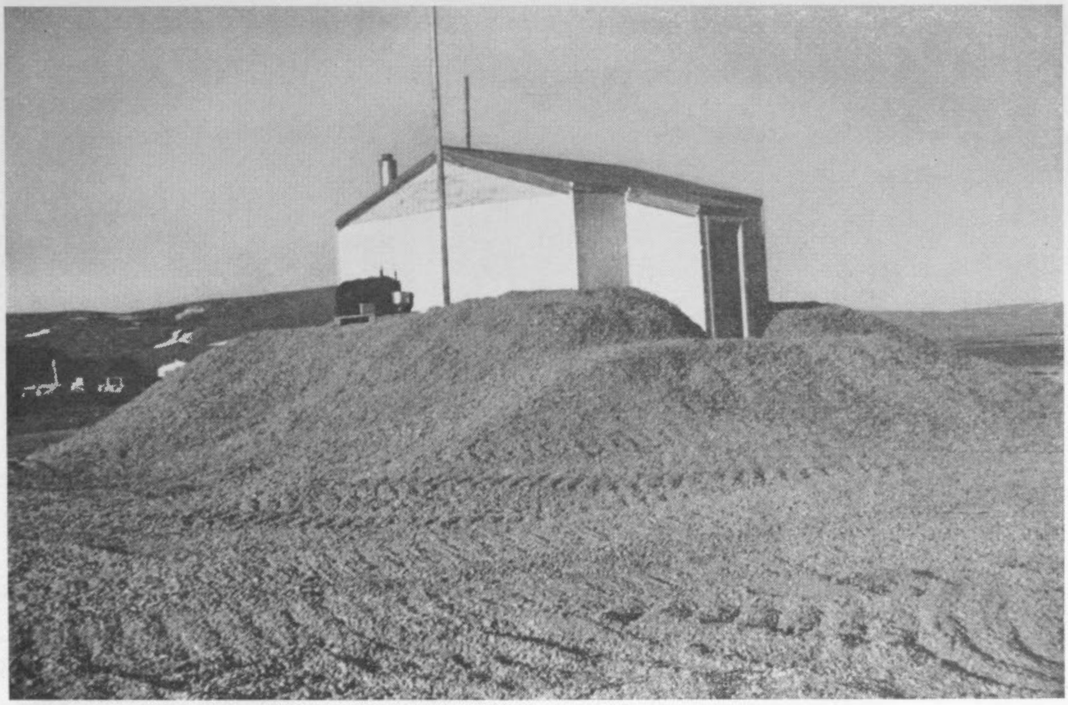


FIGURE 8—Recorder building completed. Note the oil reservoir and chimney of the oil-fired space heater.

INSTALLATION OF INSTRUMENTS

The heavy construction being completed, the installation of the seismometers and recording apparatus was begun. The short-period seismometer was set up on the bedrock and adjusted to a period of 1 second. It was connected by means of the buried cable to the Micro Moll galvanometer having a period of 0·3 second. The long-period seismometers were set up at 90 degrees to each other to record the north-south and east-west horizontal components of any earthquake that might be detected. Both were adjusted to have periods of 15 seconds and connected to galvanometers with the same periods. The trace obtained was confused by galvanometer wandering and after several days the pendulums of the seismometers had either moved considerably away from their centred positions, or were resting against the pendulum clamp. The records indicated that better temperature control and a more solid foundation for the seismometers were required.

The nature of the bedrock presented a problem in itself. The rock surface was saturated with water and badly broken; when a heavy weight was placed on the surface, small rivers of water oozed from the many fractures, outlining thin flakes of rock varying in size from pieces as small as a penny up to slabs a foot or two square. This flaky surface was stripped off, but the underlying material was in the same condition. It seemed probable that each leg of the seismometer was resting on a different island of rock. The small effect contributed by these flakes was almost entirely eliminated by pouring a concrete pier 2 feet wide, 3 feet long, and 1 foot deep for each horizontal seismometer.

Better temperature control was obtained in the instrument vault by insulating the walls with 4 inches of rock wool and lining the inside with masonite. Two 500-watt strip heaters and a thermostat set at 50° Fahrenheit were connected in series across the 220-volt line. Temperature control was further improved by insulating the instrument

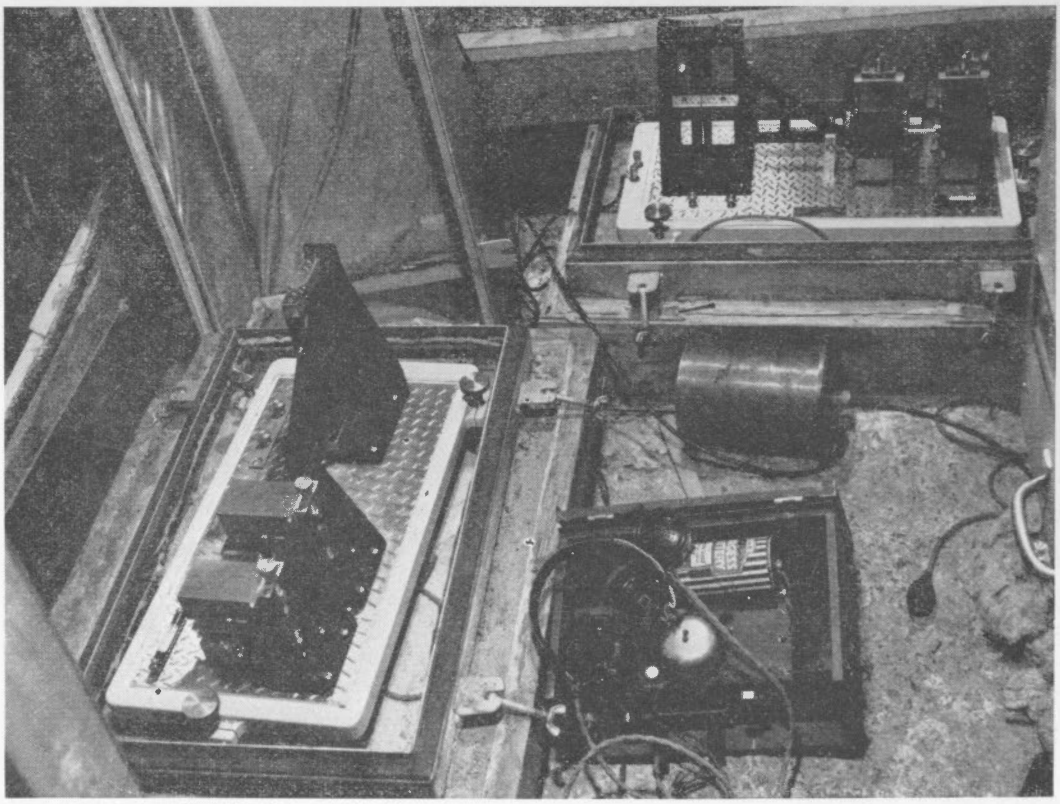


FIGURE 9—Interior of the instrument shelter. The long-period horizontal seismometers are mounted on their individual piers, the Willmore seismometer rests directly on the bedrock. The telephone for communicating with the recording building is shown in the foreground. Note the seismometer case insulated with fibreglass.

cases. The bottom was cut out of the steel base plate, and the sides were cemented into the pier. The insulated top was clamped down over the seismometer. The records obtained after the addition of temperature control and the piers were entirely different from those preceding. There was no sign of galvanometer wandering, and during two weeks the seismometer pendulums had drifted only slightly from their central position.

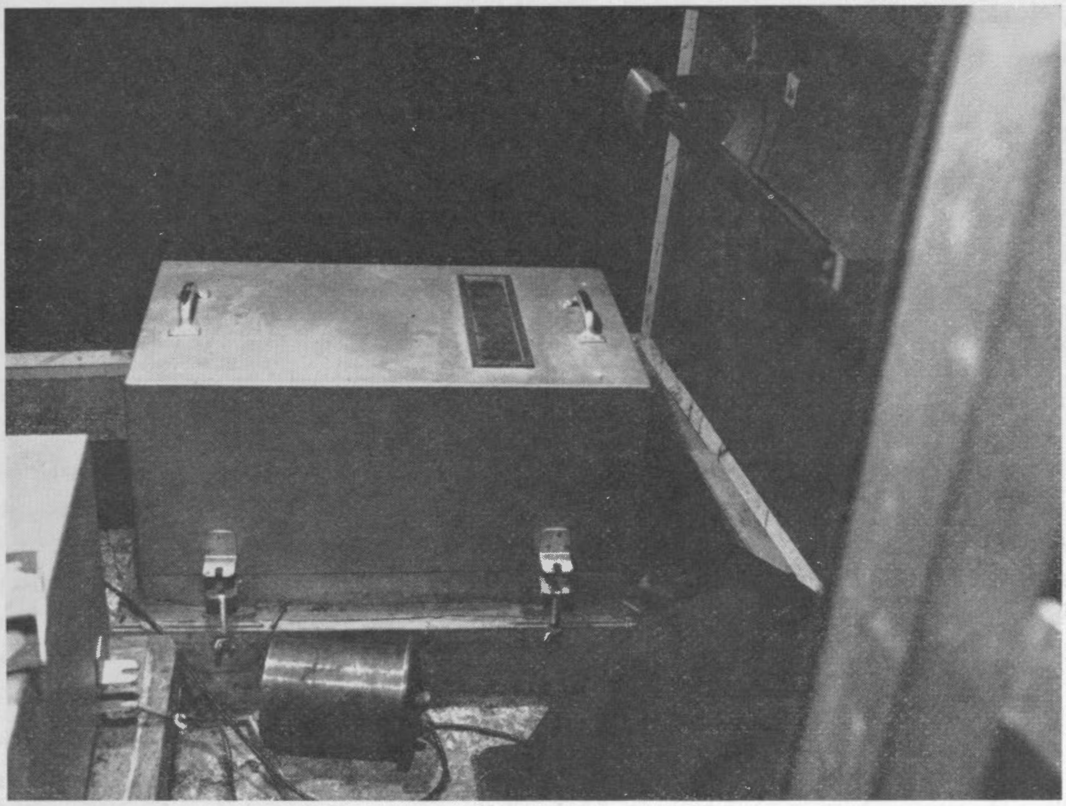


FIGURE 10—Interior of instrument shelter with insulated cases in place. Note the reflecting heater on the wall.

The instrumentation of the station was varied from time to time throughout the course of the first winter's operation. The long-period horizontals were tested with galvanometers of 6-second and 22-second periods, and the Willmore seismometer and 1·4-second Sprengnether vertical system were used at various times. The purpose of these variations was to determine the best recording system, but care was taken to keep the station in operation at all times so that its routine functions could be maintained. The 1·8-second Sprengnether horizontals were never used, as the long-period instruments proved satisfactory.

The geographical position of the instruments was accurately determined by the Topographical Survey of Canada. The co-ordinates of the bedrock on which the seismometers are set up are given as latitude 74°41′N, longitude 94°54′W. The elevation of the detectors is about 5 metres above mean sea-leavel.

THE ROUTINE OPERATION OF THE STATION

On August 29, 1950, with the completion of the installation, the first step was taken towards making Resolute Bay a first-class station for recording teleseismic disturbances. After a brief testing period, arrival times for P, S, and other clear phases were being sent to Ottawa and the United States Coast and Geodetic Survey in the form of a self-checking message. Where possible the P-phases are also classified as compressional or dilatational. Upon receipt of the Coast Survey epicentral cards the records are re-read and a bulletin prepared; the records are then sent to Ottawa for storage.

The location of the station provides an opportunity for the study of problems peculiar to that area, as for example, the seismicity and microseismic activity of the eastern Arctic islands, possible disturbances due to ice movement, and the operation of seismometers on permafrost. These topics will be dealt with in a later section in which the special investigations undertaken at the Resolute Bay Observatory are described.

As yet, there have been no difficulties with equipment which are peculiar to Arctic conditions. Once good temperature control had been established and the problems posed by the fractured bedrock had been overcome, no serious operation problems remained.

The radio time signal from WWV is used for rating the chronometer. This signal is particularly valuable as it is transmitted over a wide range of short wave frequencies, one of which can nearly always be detected with sufficient signal strength to trigger the timing relay. The signal received when the four hundred cycle note returns to indicate the beginning of a specified 5-minute period, is amplified to operate a relay in the plate circuit of the amplifying stage. This relay is in series with the lamp relays of the recorder. Consequently, both the chronometer minute marks and the WWV reference dashes are indicated consecutively on the seismogram.

Part of the error incurred when calculating arrival times arises because of variation in the cycle of the electrical power furnished to the observatory. As the recording drum is driven by a synchronous motor, the cycle of the power supply determines the rate of rotation of the drum, which in turn regulates the distance between chronometer minute marks. At Resolute the cycle varies from fifty-six to sixty-four cycles per second, depending on the line load. As these variations may occur often during a short period of time an attempt was made to obtain a more accurate sixty-cycle source.

This took the form of a power oscillator. Essentially the oscillator was a multivibrator with two stages of power amplification. The wave form was determined by careful selection of values for condensers and choke coils used in the multivibrator circuit. A bias control on the multivibrator determined the output frequency which was set at sixty cycles per second. Unfortunately, though the rate of the oscillator was more reliable than the station power, its cycle could not be held fixed but kept drifting higher with tube age. The cycle was adjusted to sixty c.p.s. by altering the bias but the steady increase finally overruled this control. Since supply problems made it impossible to change the tubes at frequent intervals, and since excessive paper speeds could not be tolerated because of the drain on the stock of photographic paper, the oscillator was discarded and the regular power supply re-installed. This system allows time to be measured to the nearest second or perhaps the nearest half-second.

It was mentioned earlier that experiments were conducted to determine the best operating period of the horizontal seismometers. Serious disadvantages were evident when using the 7- and 22-second system, but the 15-second arrangement was quite satisfactory. At the lower range, microseisms were recorded frequently with amplitudes that obscured any other seismic disturbance on the record. On the other hand, at the higher range the seismometer was unstable, being very sensitive to tilt; over a period of several weeks the boom drifted well off the calibration adjustment, often coming to rest against the boom clamp. The intermediate 15-second range was stable and for the most part free from severe microseismic disturbances.

The final instrumentation consisted of a Sprengnether short-period Series DH vertical seismometer with matching Leeds and Northrup galvanometer. The system was adjusted for critical damping, the seismometer and galvanometer operating at the same period of 1·4 seconds. In addition there are the two long-period Sprengnether Series H horizontal seismometers oriented to record the north-south and east-west components of motion. Operating under the same conditions as the short-period system, the final period of the north-south is 14·1 seconds, and of the east-west 13·5 seconds. Direction of first motions were noted, relating trace displacements to the direction of ground motion.

The table below gives the constants of the instruments.

Instrument Constants of the Resolute Bay Seismological Observatory

Component	Instrument	Period (seconds)	Magnification	First Ground Motion
Z	Sprengnether Series DH Vertical	1·4	10,000 c.a.	Compression-up seismogram
NS	Sprengnether Series H Horizontal	14·1	1,600	North-up seismogram
EW	Sprengnether Series H Horizontal	13·5	1,600	East-up seismogram

Seismograms are read once a day at the Resolute station and a radio message sent out immediately if any earthquakes have been recorded. Unless communication conditions are poor the message will arrive in Ottawa less than 24 hours after it was compiled at Resolute. At Ottawa the message is relayed at once to the United States Coast and Geodetic Survey.

Initially the messages were sent out simply as a series of numbers, but it was found that the signals were frequently garbled in transmission. Code messages were, therefore, resorted to, the code being a modification of one used some time ago by the United States Coast and Geodetic Survey. The message form is shown in Figure 11, and its use will be illustrated by an example. Suppose the following message is to be transmitted:

P 17d: 09h: 24m: 06s
S 17d: 09h: 30m: 27s
P 18d: 04h: 29m: 12s

The number of phases to be transmitted is indicated under column 16 by the number 3. The first phase is a P, indicated by the number 1 under column 17. Next follows the time in days, hours, minutes and seconds, care being taken to include a zero if any number has a single figure. The information on the second phase begins in column 26, the number 2 indicating that the phase is an S. If there had been an unidentified phase it would have been indicated by the number 3.

The numbers are divided into groups of five by the heavy vertical lines. These groups of five are written down, one under the other, in columns 1 to 5. For the section "Vertical Check" all six numbers in column 1 are added; the last number, seven, of the total twenty-seven obtained, is inserted in column 6. Only the last number of the totals is significant, the others being dropped. Thus, adding columns 2, 3, 4, and 5 respectively, we obtain the entries for columns 7, 8, 9, and 10. For the horizontal check the numbers in columns 1 to 5 are added horizontally, the first row of these providing the entry for column 11, and so on down to column 15. The last row of numbers is not added.

The complete number message is transformed to a series of five-letter words, using the key provided on the form. The complete message as received in Ottawa would read as follows:

Resolute Bay Nov. 18/51.
P_c 17 09 24 06
S 17 09 30 27
P_d 18 04 29 12
SGNTT/DAUGM/GAASW/UDKWN/DASWU/GWDSA/ATWKD/UADWW Stop.

The subscripts c and d, indicating a compression and dilatation, respectively, are not included in the self-checking code. Both the numbers and the code are sent, thereby providing a double check.

SPECIAL INVESTIGATIONS AT RESOLUTE BAY

With the completion of the instrumental installation at Resolute Bay consideration was given to the study of special problems. The seismicity of the eastern Arctic islands, seismic disturbances caused by shifting ice, and the use of perma-frozen ground as a foundation for seismometers were three topics of particular interest to this northern observatory. A qualitative study of microseisms was also undertaken for a period of 8 months. These investigations have served to emphasize the advantages and disadvantages of the present system of detectors. It is hoped that additional seismometers will soon be available to enable a more complete investigation of the topics that are discussed below.

NEAR EARTHQUAKES IN THE EASTERN ARCTIC ISLANDS

Prior to the establishment of the seismic observatory at Resolute Bay, reports of near earthquakes from inhabitants of islands in the eastern Arctic suggested that the region might be quite active. During the latter part of 1949, and the first months of 1950, no less than seven reports of tremors were received from personnel at the weather station on Ellef Ringnes Island.

SEISMOLOGICAL MESSAGE

P-phase = 1
S-phase = 2
Other-phases = 3

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
							Vertical check of	words in message			Horizontal check of	words in rows 16 to	40 inclusive			No. of phases	Phase	day	day	hour EST	hour EST	minute	minute	second	second	Phase	day	day	hour EST	hour EST	minute	minute	second	second	Phase	day	day	hour EST	hour EST	minute	minute	second	second	Phase	day	day	hour EST	hour EST	minute	minute	second	second
	3	1	1	7	0																																															
	9	2	4	0	6																																															
	2	1	7	0	9																																															
	3	0	2	7	1																																															
	1	8	0	4	2																																															
	9	1	2	0	0																																															
Data						7	3	6	8	8	2	1	9	3	5	3	1	1	7	0	9	2	4	0	6	2	1	7	0	9	3	0	2	7	1	1	8	0	4	2	9	1	2	0	0							
Letters						S	G	N	T	T	D	A	U	G	M	G	A	A	S	W	U	D	K	W	N	D	A	S	W	U	G	W	D	S	A	A	T	W	K	D	U	A	D	W	W							

Message

Code	1	2	3	4	5	6	7	8	9	0
	A	D	G	K	M	N	S	T	U	W
	Andrew	Daniel	George	Kate	Mary	Norman	Sam	Tom	Union	William

FIGURE 11

Several systems of electro-magnetic seismographs, some of them in operation only for a period of several weeks, were installed at the station for studying local seismicity. The most satisfactory results were obtained when using a Willmore seismometer with a period of 0·3 second coupled to a Micro Moll galvanometer with a period of 0·3 second.

Although considerable activity was anticipated, the study of seismograms did not justify these expectations. Over a period of one year, five local tremors have been well recorded; other disturbances on the records may possibly be caused by local earthquakes. The P and S phases for these disturbances were well defined and additional i-phases were noted in both the P and S groups. Epicentral distances varied between 280 and 725 kilometres from the Resolute station. It may be that the earlier disturbances reported from Ellef Ringnes Island were, in fact, not earthquakes but resulted from ice shifting in the nearby bay. Though the Ellef Ringnes area has been occupied for some years, it is worth noting that all seven reports were issued over a period of 3 months from one settlement. No reports have come from other inhabitants of the eastern Arctic during the past six or seven years.

Sea Ice as a Source of Ground Noise

During the winter months at Resolute Bay the short-period records were carefully scanned for spurious activity that might be attributed to the movement of the sea ice under the influence of the tide. Though random noises were identified on the trace, there was little to indicate that this effect stemmed from tidal, or other forces, acting on the ice. Since the detectors are situated less than half a mile from the ocean, it was decided to undertake a further test during the month of May, when the sea ice attains its maximum thickness of approximately 6 or 7 feet.

The seismic detecting system used for studying ice noise was the same as that used for recording local tremors. In addition, a tide gauge equipped with a pen recorder was mounted on the ice to provide a graph of sea-level against hour of the day. The range of tide, its rate of change, and the time of low and high water were noted for each day.

An examination of the seismograms for the test period revealed bursts of high-frequency disturbances lasting from 2 to 15 seconds. The energy involved was small, for these bursts of spurious noise were seldom perceptible on the short-period Sprengnether seismometer. The number of disturbances varied from 25 to 75 a day and a count was made of the number of distinct disturbances occurring during each half-hour period. A comparison of seismic data with the tide curve suggested that the ground noise was not obviously related to the amplitude, slope, or phase change of the tide graph. The high-frequency vibrations were recorded almost entirely between 09:00 and 21:00 local time (Central Standard Time) during each day of the test period. There appeared to be no relationship between the number of disturbances recorded, and the rate of change of the tide; neither was there any indication of a change in the time during which noises were most frequent to coincide with the phase shift of the tide curve. No suitable explanation is put forward to justify these disturbances, but a longer testing period may show they are present the year round and are possibly associated with the freezing and thawing of the active layer that covers the permanently frozen ground.

INSTALLATION OF SEISMOMETERS ON PERMAFROST

Normally, seismometers are set up on concrete piers that are in contact with bedrock; on some occasions the seismometers may be mounted directly on the bedrock. In certain instances it becomes desirable to establish an observatory in a location where bedrock is not easily accessible and in such cases well-consolidated materials often prove quite satisfactory for certain types of instruments.

The Arctic climate provides yet another medium that may provide a suitable base for detectors and that, in its undisturbed state, will transmit seismic radiation almost as well as bedrock. This medium is permafrost, a frozen layer made up of constituents varying from a mixture of washed gravel and ice, to frozen muskegs saturated with ice lenses. In the eastern Arctic the permafrost almost invariably extends to bedrock and when protected from additional heat its coefficients of compressional and shear stress should be comparable to those of concrete for the purpose of installing seismometers.

Experiments were conducted with a short-period Sprengnether vertical seismometer set up on permafrost. The installation was of a temporary nature but results suggest that this medium could be used satisfactorily as a site for seismometers. Rigid contact with the permafrost was achieved by hammering three 4-foot lengths of 2½-inch pipe into the ground. The seismometer was mounted on a steel plate resting on these pipes. This crude arrangement proved adequate for recording almost all the earth tremors reported by the United States Coast and Geodetic Survey during the period that the seismometer was operating on permafrost. On removing the steel pipe some two months later, it was evident that the frost level had already risen several inches.

Since testing indicates that permafrost could be used as a base for seismometers, provided care is taken not to supply heat to the frozen layer, it is well to consider the most suitable way of constructing a surface for mounting the instruments. One method of obtaining a suitable table would be to drive steel pipes well into the frozen ground and then to pour a concrete pier around the extended pipe so as to form a slab floating above ground. Care in insulating beneath the table top so formed, and around the pipes, would allow the frost layer to rise. This type of construction would probably provide a more stable pier than one poured into a deep excavation and subjected to the forces acting at the surface of the frozen layer. No tests have been made to determine the stability of permafrost with regard to operating a long-period horizontal seismometer. Indeed, this type of pier might prove unsatisfactory for systems sensitive to tilt but should be quite suitable for most types of short-period instruments as well as for long-period vertical seismometers.

MICROSEISMIC STORMS AT RESOLUTE BAY

Microseismic storms have been well recorded at Resolute Bay on the two long period Sprengnether horizontals and to a lesser extent on the short-period vertical. The variation of amplitude and period of microseisms show no relationship with changes of barometric pressure recorded at the Resolute Bay weather station. There are, however, problems and opportunities for which this station is particularly well situated.

Over the past years many mechanisms have been proposed as the cause of the microseisms; the common theme of nearly all hypotheses is that radiation is closely associated with atmospheric disturbances over large bodies of water. During much of the year, the Arctic seas are covered with ice, and the microseismic pattern to be expected at Resolute Bay was unknown.

Inspection of seismograms from Resolute Bay suggests that a definite relationship exists between microseismic storms and meteorological disturbances to the south having their low pressure areas over ice-free water. There does not seem to be any relationship between the microseismic amplitudes and the prolonged high winds so common in the Arctic. Whether this is due to the presence of the ice or to some other factor is not yet definitely established.

The study of microseisms at Resolute Bay is hampered by the lack of a long-period vertical seismometer. It is anticipated that this lack will be filled in the near future. With this in mind, arrangements are being considered to correlate observations of microseismic amplitude and period with hour of the day for a 2- or 3-month period, with similar studies to be organized at Ivigtut, Scoresby-Sund, Iceland, Bergen, Upsala, Copenhagen, Kew, and Palisades. It is hoped that important conclusions concerning microseismic mechanisms may be deduced from a progressive study of microseisms, atmospheric conditions, and other factors for this large area.

ACKNOWLEDGMENTS

The early completion of the seismic observatory is largely due to the assistance of the Royal Canadian Air Force, whose Air Transport Command flew more than 12 tons of supplies into Resolute Bay in time to begin construction in July 1950. Thanks are due to Mr. S. W. Dewar, Officer-in-Charge of the weather station, who made available all the facilities at his disposal, as well as to the Ionosphere Station at Resolute which sends the seismic radiograms to Ottawa with minimum delay. Finally, the interest and ready help of Mr. Rodney Andrews, Seismologist-in-Charge of the Resolute Observatory for the year 1951-1952, contributed greatly towards the success of the project.

CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
DOMINION OBSERVATORIES

PUBLICATIONS

OF THE

Dominion Observatory

OTTAWA

Vol. [illegible], No. 3

CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
DOMINION OBSERVATORIES

PUBLICATIONS
OF THE
Dominion Observatory
OTTAWA

Vol. XVI, No. 3

Canadian West Coast Earthquakes, 1951

BY

W. G. MILNE AND F. LOMBARDO

EDMOND CLOUTIER, C.M.G., O.A., D.S.P., OTTAWA, 1953
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY

Canadian West Coast Earthquakes, 1951

BY

W. G. Milne and F. Lombardo.

ABSTRACT

Three station triangulation of local earthquakes in the British Columbia Coast regions was initiated in August, 1951, making use of short period Benioff and Willmore seismographs. The three stations were located at Victoria and Alberni on Vancouver Island and at Horseshoe Bay on the mainland. Seventy-four earthquakes were recorded in a five months' period and it was possible to determine epicentres for 27. Some indications were given of areas of localized activity but it is expected that at least another year's operation will be required before such areas are at all clearly defined. Tables of epicentres and times are given and the stations and equipment are described.

INTRODUCTION

In June of 1948 a Benioff vertical short-period seismograph was set up at the Dominion Astrophysical Observatory in Victoria to add to the Milne-Shaw horizontal instruments then in service. The main purpose of the additional instrument was to record the local earthquakes which were assumed to be occurring in the vicinity of Vancouver Island, British Columbia. Between that date and January of 1951, 199 earthquakes were recorded as having originated along the strip of coast from the northern Queen Charlotte Islands south to Oregon. This total was sufficiently great to warrant an increase in the seismograph stations in the area.

It was decided that a triangulation network consisting of two stations in addition to Victoria should be set up in 1951. The two stations were to be equipped with three-component, short-period, Willmore-Sharpe seismometers recording on Sprengnether recorders. This present report deals with the setting-up of such a system, and the earthquakes recorded in 1951. Subsequent reports are proposed each year to carry along a complete seismic history of the area. In addition, a past seismic history of the area is being prepared. It is hoped that this will be sufficiently complete to warrant publication in the near future.

THE NEW STATIONS

The expanded program in British Columbia was made possible by the completion of the field work of the rockburst project[1]. In that work a technique had been developed for housing seismograph stations in portable buildings and two of the buildings with the necessary seismometers and recorders became available in the spring of 1951. After being overhauled in Ottawa the buildings were crated and shipped to British Columbia by rail. All instruments for the two new stations were transported to the west coast by truck.

Alberni

With the co-operation of the School Board of District 70, Port Alberni, a location behind the Old Gill School in Alberni was made available for one of the new seismic

---

[1] Hodgson, J. H., "A Seismic Survey in the Canadian Shield", Publications of the Dominion Observatory, in preparation.

stations. This location is on a large flat outcrop of basic volcanic rock. The recording hut foundation construction was carried out without difficulty. The seismometer hut was erected 150 feet distant on the same outcrop. At Alberni where it rains a great deal in the fall and winter good water-proofing is needed for the hut. The necessity of a location some distance from a main road was emphasized in December, when a bridge was washed out on the main highway and heavy traffic was diverted over the secondary road passing within a hundred yards of the seismograph. The records were greatly disturbed at busy times.

The station at Alberni commenced operation on August 17th and was cared for during the summer by a student assistant. In September a local operator was trained to carry on the work. Each week the records are mailed to Victoria for reading at the Dominion Astrophysical Observatory.

Horseshoe Bay

At the Horseshoe Bay location permission was granted by the North West Telephone Company to erect a seismic station on a ledge on the mountain overlooking Horseshoe Bay, West Vancouver. The ledge is an outcrop of granitic rock, possibly granodiorite. The exposed surface is about 10 feet square sloping down at about a thirty degree angle. Before the hut foundation could be poured with concrete, a solid cement floor was built. A trolley system was devised to carry concrete, in buckets, up the steep slope. To allow for the unusually slow process of placing the concrete, a retarder or slow set was added to the ready-mix concrete. The foundation and piers were poured on top of the solid floor. A seismometer hut was erected approximately 80 feet from the recorder hut. At this station the traffic noise is negligible. However, a car-ferry docking in the bay area disturbs the records for some three minutes four times a day. It would appear that the boat actually rams into the piles driven into the floor of the bay, and this sets up a vibration in the ground. At Horseshoe Bay the seismometer hut is in a group of trees and following a heavy snowfall the seismometers are disturbed by what is thought to be big clumps of snow falling from the tree branches.

Operation of the Horseshoe Bay station was carried on for a few months by one of the Department's technicians, who in turn trained a local operator. As at Alberni, the records are mailed to Victoria to be interpreted.

Instrumental Arrangements

A word about the seismometers might be included, for little literature is available on the Willmore-Sharpe instrument. The original instrument was designed by Willmore for use in South Africa. With his permission copies were made for the Canadian government by the Sharpe Instrument Company of Toronto. They were first used in the recording of rockbursts in Eastern Canada[1] where they proved very successful. The seismometer design is a moving coil suspended by tension springs in the field of a strong pot-type magnet. Vertical and horizontal instruments are identical except that the vertical has an extra flat spring in its suspension system. The free period of the moving coil is 1/4 to 1/3 second; damping is slightly less than critical. The seismometer is operated with a galvanometer whose free period is of the order of 1/20 second. The system is extremely sensitive to short period vibrations such as those set up by an earthquake within a two-hundred kilometre radius. However, it is felt that the overall period is too short and experiments are being conducted to lengthen this period. The recording device is a standard Sprengnether microseismic recorder.

Time control for all three stations is obtained through the local CBC Vancouver broadcasting station, CBU, which transmits the 18 hours GMT radio signal from CHU, Ottawa. The regular shortwave CHU channel cannot be received on the west coast. The CBC signal is carried to Vancouver from Ottawa by land-line which undoubtedly introduces some lag in the signal, but because all three stations use the same radio signal no difference in relative time need be taken into account. This time lag on the Ottawa-Vancouver land line is being measured.

The pertinent information on the three British Columbia stations is given in Table 1.

TABLE 1

Victoria: August 1st to December 31st inclusive
(V) φ = 48° 31′ 14″ N.
λ = 123° 24′ 56″ W.
Benioff short-period vertical seismograph.

Horseshoe Bay: August 6th to December 31st inclusive
(HB) φ = 49° 22′ 39″ N.
λ = 123° 16′ 33″ W.
Willmore-Sharpe north-south, east-west, and vertical component short-period seismographs.

Alberni: August 11th to December 31st inclusive
(A) φ = 49° 16′ 14″ N.
λ = 124° 49′ 18″ W.
Willmore-Sharpe north-south, east-west, and vertical component short-period seismographs.

EPICENTRE LOCATIONS

Table 2 lists the earthquakes recorded on the network stations from August 6 until the end of 1951. Those earthquakes which have been recorded on all three stations have been located as accurately as possible. The few tremors which appear to be associated with the edge of the continental shelf in the Pacific Ocean are not as precisely located as are those within the triangle of the stations. However, the Pacific earthquakes are occasionally located by the United States Coast and Geodetic Survey epicentre program. Those earthquakes south of Victoria, and out of the triangle, cannot be precisely located from Canadian data alone.

TABLE 2—1951 EARTHQUAKES

No.	Date	Origin Time GMT	Lat. N.	Long. W.	Intensity	Arrival Times of P-phase			Distance			Remarks
						Victoria	Horseshoe Bay	Alberni	V	HB	A	
			° ′	° ′						kms		
1	Aug. 8	12 43 07	49	129	......	12 44 05	12 44 04·4	....	...	...	...	U.S.C.G.S. location
2	Aug. 8	14 13 08	49	129	......	14 14 06	14 14 08·1	....	...	...	...	U.S.C.G.S. location
3	Aug. 9	....	....	....	......	....	20 49 24·0	....		35		
4	Aug. 10	....	....	....	......	....	15 28 14·0	....		28		
5	Aug. 13	18 07 36·6	49 07·5 or 49 05	123 42·0 or 122 58	II	18 07 48·3	18 07 43·8	....	71	44		Straits of Georgia off Nanaimo or off Ladner, B.C.
6	Aug. 13	22 30 29·5	....	....	I	22 30 49·5	22 30 36·9	....	...	...	...	Same area as No. 5 probably
7	Aug. 13	....	....	....	......	23 44 30·8	....	....	24			
8	Aug. 17	....	....	....	......	....	5 30 05·2	....	...	...	...	
9	Aug. 17	23 40 43·9	49 13·2	122 35·8	III	23 40 59·8	23 40 51·4	23 41 09·9	102	43	163	North of Fraser River, west of Port Coquitlam, B.C.
10	Aug. 18	11 35 04·9	48 38·2	122 40·5	I	11 35 14·4	11 35 20·3	11 35 32·4	57	94	173	Orcas Islands
11	Aug. 18	18 37 10·5	48 37·5	122 56·7	I	18 37 17·1	18 37 25·0	18 37 35·8	36	88	154	Orcas Islands
12	Aug. 20	9 53 56·4	48 02·9	123 42·2	I	9 54 04·4	9 54 21·0	9 54 21·5	56	154	156	West of Port Angeles
13	Aug. 22	10 22 52·2	48 41·8	123 39·8	I	10 22 57·2	10 23 05·7	10 23 10·0	25	80		On South Vancouver Island
14	Aug. 22	....	....	....	......	13 39 01·1	13 39 02·6	13 38 45·6	...	...	...	Off west coast of Vancouver Island
15	Aug. 23	7 54 06·9	48 29·8	124 57·7	III	7 54 26·2	7 54 33·0	7 54 21·4	118	166	88	Western Juan de Fuca Strait
16	Aug. 23	....	....	....	......	....	14 33+	....	...	...	...	May not be seismic
17	Aug. 25	14 01 07·3	43 37·4	123 32·2	II	14 01 10·2	14 01 21·9	14 01 26·8	14	88	119	Bamberton blast (?)
18	Aug. 27	....	....	....	......	....	23 10 37·7	....	...	...	...	
19	Sept. 5	....	....	....	......	....	....	0 20 30·5	...	...	...	Very near Alberni
20	Sept. 5	....	....	....	......	....	6 03 48·5	....	...	...	...	
21	Sept. 6	4 28 37·3	48 40·6	123 23·5	III	4 28 40·9	4 28 50·2	4 28 58·1	21	78	127	South of Coal Island
22	Sept. 10	(12 54 04·6)	(48·4)	(129·2)	I	12 55 02·8	....	12 54 50·8	423		326	Off west coast of Vancouver Island
23	Sept. 13	4 54 46·7	49 13·8 or 50 04	126 03·5 or 125 05	II	4 55 18·8	....	4 55 02·1	215		91	Near west coast of Vancouver Island or North west of Powell River
24	Sept. 13	....	....	....	......	6 21 08·9	....	6 20 57·7	...	...	...	
25	Sept. 14	7 07 25·4	49	128 30	IV	7 08 18·2	7 08 21·0	7 08 06·1	388	391	278	U.S.C.G.S. location
26	Sept. 20	....	....	....	......	....	....	20 53 12·5	...	...	...	
27	Sept. 21	....	....	....	......	11 23 16·8	11 23 25·6	....	...	...	...	
28	Sept. 21	....	....	....	......	19 36 29·3	....	....	...	...	...	
29	Sept. 22	10 16 56·0	48 00·0	127 00·0	III	10 17 37·5	10 17 40·3	10 17 30·6	302	345	243	U.S.C.G.S. location
30	Sept. 26	....	....	....	......	....	....	15 35 45·0	...	...	...	
31	Sept. 27	19 24 12·4	49	129	VI	19 25 08·8	19 25 10·8	19 24 57·0	410	426	312	U.S.C.G.S. location

32	Sept. 27							19 31 35·0		Same as No. 31
33	Sept. 27							19 44 08·1		Same as No. 31
34	Sept. 28							15 19 20·0		
35	Sept. 30					8 32 24·5			45	
36	Sept. 30					13 31 39·1		13 31 39·6		Off coast of Oregon (?)
37	Sept. 30					14 50 16·7		14 49 57·6		
38	Oct. 1					14 06 21·8				
39	Oct. 4	23 27 19·4			II	23 27 38·8	23 27 49·2	23 27 53·1	116 204 216	Off coast of Oregon
40	Oct. 5				II	16 13 43·3		16 13 16·9	416	Off west coast of Vancouver Island
41	Oct. 7	11 59 31·3	47 40	123 30	III	11 59 39·0	11 59 53·4	11 59 55·2	82 180 194	South of Port Angeles, Wash.
42	Oct. 8					5 12 37·4				
43	Oct. 9	22 59 27·7	48 10·8	122 46·2	IV	22 59 38·0	22 59 50·5	22 59 57·6	62 140 195	North of Port Townsend, Wash.
44	Oct. 13		43 30	121·7		19 46 29·5				U.S.C.G.S. location
45	Oct. 19							00 18 58·7		Very near Alberni
46	Oct. 26	23 41 26·3	49 01	122 08	II	23 41 44·1	23 41 41·6	23 42 05·5		Near foot of Mount Baker, Wash.
47	Oct. 27					15 24 04·6		15 23 55·9		
48	Oct. 28					14 52 23·5		14 52 18·7		
49	Nov. 2							23 02 08·2		Very near Alberni
50	Nov. 4	3 36 11·2	48	124	III	3 36 23·2	3 36 36·6		73 156	South of Victoria
51	Nov. 7	9 16 43·8	49 00·0	123 44·9	II	9 16 53·7	9 16 52·9		59 55	North west of Ladysmith, B.C.
52	Nov. 9					14 55 37·7				
53	Nov. 14	8 23 30·4	49 02·4	123 41·1	I	8 23 45·7	8 23 43·6		62 48	North east of Ladysmith, B.C.
54	Nov. 14					19 27 55·0				
55	Nov. 14					22 56 17·2				
56	Nov. 20						15 06 45·0			
57	Nov. 24	14 40 45·7	47 52·6	124 21·8	I	14 41 02·3	14 41 14·9	14 41 11·5	102 190 160	Washington state
58	Nov. 29	0 24 35·3	48 54·6	122 27·9	II	0 24 48·7	0 24 48·4		81 79	Foothills of Mount Baker, Wash.
59	Dec. 7	20 20 19·1	48 37·4	123 16·5	II	20 20 22·2	20 20 32·8	20 20 40·8	19 83 134	North west of Sidney Island
60	Dec. 11	18 50 25·8	49 10±	123 50·5±	II	18 50 38·9	18 50 33·8	18 50 37·5	79 49 71	Gabriola Island (See Fig. 2)
61	Dec. 11				I		18 51 40·6	18 51 44·5		
62	Dec. 11	19 44 59·2			II	19 45 11·9	19 45 06·9	19 45 11·3	78 47 74	
63	Dec. 11	19 59 43·2			II	19 59 56·3	19 59 51·4	19 59 54·6	70 50 81	
64	Dec. 12	3 06 25·3	48 36·1	123 45·8	I	3 06 30·8	3 06 40·6	3 06 42·9	27 95 107	North east of Survey Mountain
65	Dec. 13					1 08 08·6				
66	Dec. 14					19 26 41·8	19 26 49·7			
67	Dec. 14					20 02 52·1	20 02 54·2			
68	Dec. 15				I	7 01 08·1	7 01 12·9	7 01 31·4		
69	Dec. 15							23 14 50·5		
70	Dec. 18	10 46 55·6	49 10·1	125 01·2	II	10 47 17·3	10 47 16·8	10 46 58·7	139 129 21	South west of Alberni felt
71	Dec. 18					18 56 38·8				
72	Dec. 19					8 18 20·3	8 18 17·7			
73	Dec. 21						8 13 18·0	18 13 39·5		Blast near Horseshoe Bay (?)
74	Dec. 23						1 12 53·3			Blast near Horseshoe Bay (?)

Preliminary determination of epicentres is made on the basis of the difference of first P-arrivals at the three stations. Assuming the velocities of P_1 and P_n to be, respectively, 6.246 and 8.203 km/sec. as found in the Canadian Shield it is possible to construct a series of loci for any pair of stations corresponding to differences of -4, -2, 0, 2, 4, etc., seconds in P-arrivals. By measuring the difference in arrival time the earthquake is placed on one of these lines. Similarly a second set of curves, for a different pair of stations, locate the epicentre with respect to that pair. The epicentre must lie in the zone of intersection of these sets of curves. A third set of curves, corresponding to the third pair of stations, is necessary to remove the ambiguity in the two positions obtained using two stations only. This preliminary epicentre is then adjusted to make all three stations fit as well as possible an assumed origin time. As a final check the S-phases are read where possible and are used to confirm the location found above.

Where the earthquake is recorded on two stations only, two positions are obtained for an epicentre, such as numbers 5 and 23 in Table 2. One of these can occasionally be eliminated by careful study. Those seismic disturbances, which are recorded at one station only, are listed to make this history complete.

Table 2 also gives, where possible, an estimate of the intensity of each earthquake on the modified Mercalli scale. There is no great accuracy claimed for this rating, rather it is meant to give the order of relative intensities of the disturbances. For those earthquakes which are given a magnitude by the United States Coast and Geodetic Survey, an intensity rating is obtained from conversion tables (Gutenberg and Richter, 1942)[2]. Well recorded disturbances, which are known to be blasts, are listed and labelled accordingly.

DISCUSSION

If the 74 earthquakes recorded in the five-month interval August to December can be taken as an average number, one could expect to record approximately 180 earthquakes a year. This is a few more than past recording with the Victoria Benioff alone would indicate, but not unreasonably so. The more sensitive Willmore-type seismometers probably account for all the extra and this suggests 1951 was not a sub-normal year. There were no major earthquakes in 1951.

Located epicentres in Table 2 are shown in the maps of Figures 1 and 2. A preliminary study of the map suggests that no definite pattern has yet been established. However, it must be admitted that there are certain areas somewhat more active than others.

Probably that region at 128 to 129 degrees west longitude where one would expect to find the edge of the continental shelf has been most active. These earthquakes cannot be precisely located, but in general they form a line parallel to the edge of Vancouver Island. These are the strongest of any recorded. Between this "shelf" and the Island there appear to be no earthquakes until a few kilometres off land. Here only two are found and one of these (23) only a probable location.

South in the State of Washington there are several locations, not quite where one expects to find epicentres. The earthquake felt in Victoria (No. 43) is from this general area towards Puget Sound.

---

[2] Gutenberg, B., and Richter, C. F., "Earthquake Magnitude, Intensity, Energy and Acceleration", Bulletin, Seismological Society of America, Vol. 32, 163-191, 1942.

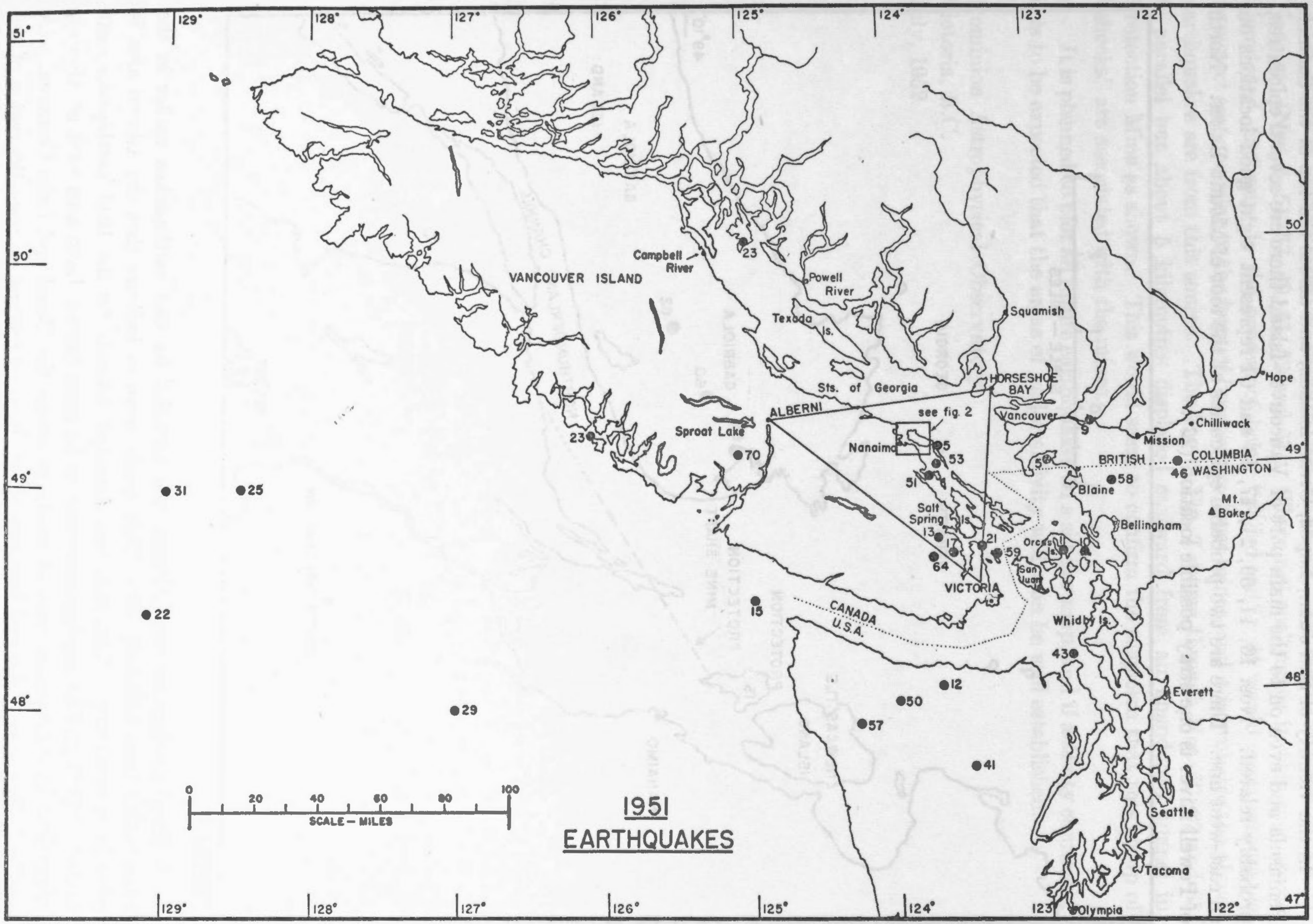

1951
EARTHQUAKES
51°
50°
49°
48°
47°
129°
128°
127°
126°
125°
124°
123°
122°
VANCOUVER ISLAND
Campbell River
Powell River
Texada Is.
Squamish
Sts. of Georgia
HORSESHOE BAY
ALBERNI
Sproat Lake
see fig. 2
Nanaimo
Vancouver
Salt Spring Is.
VICTORIA
CANADA
U.S.A.
BRITISH COLUMBIA
WASHINGTON
Blaine
Bellingham
Orcas Is.
San Juan
Whidby Is.
Mission
Chilliwack
Hope
Mt. Baker
Everett
Seattle
Tacoma
Olympia
23
23
70
31
25
22
29
15
5
53
51
13
17
64
21
59
9
5
58
46
10
43
12
50
57
41
0
20
40
60
80
100
SCALE — MILES

FIGURE 1

In the vicinity of San Juan, Lopez, Orcas Islands, and across the top of the Saanich Peninsula and even on to the main part of Vancouver Island there are several epicentres, probably related. Nos. 10, 11, 59, 21, 17, 13 and 64 represent eight good locations on an east-west line. There are two probable epicentres at the foot of Mount Baker. North of Powell River is one stray possible location (23).

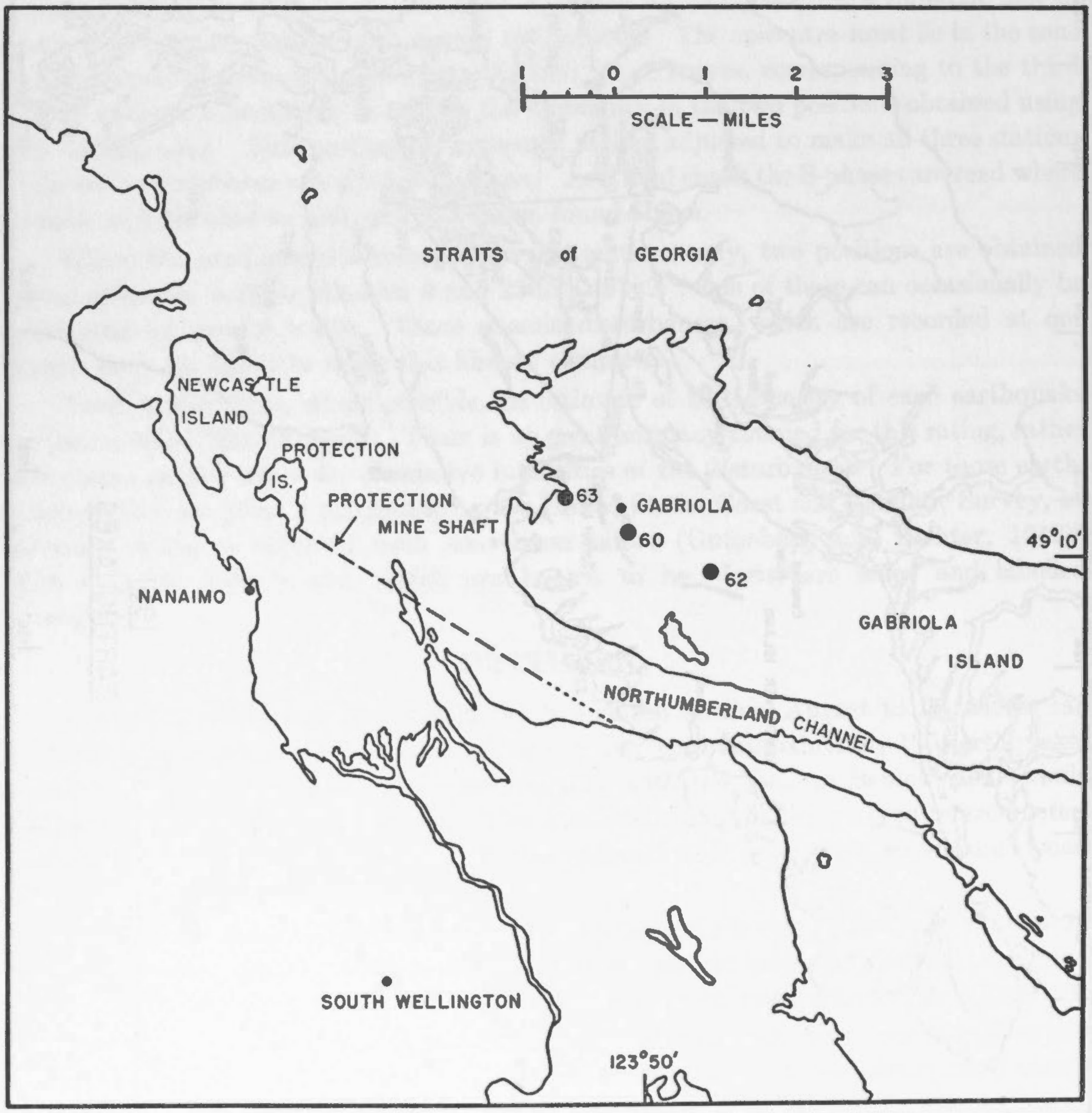


FIGURE 2

A single earthquake near Alberni was preceded by two earthquakes earlier in the spring which were definitely felt. This would seem to indicate that the Alberni area is active in a small way. This area was damaged severely by the 1946 earthquake near Comox. These smaller earthquakes seem to be from Sproat Lake area west of Alberni, rather than in a suspected zone of weakness across the Canal and Lake Cameron. (A notable feature here is the fact that there have been no epicentres near the region of the 1946 major earthquake in the northern Strait of Georgia.)

A group of earthquakes, or disturbances, have been recorded from south east of Nanaimo (Nos. 5, 51, 53, 60, 61, 62 and 63). There are coal mines in this area, some abandoned, and some in the process of being "pulled out". It would seem reasonable to expect some settling in the form of bursts from these mines, and it is probable the above earthquakes are from this source. The line in Fig. 2 drawn through Nos. 60, 62 and 63 is parallel but about 5 kilometres displaced eastward from an abandoned tunnel in Protection Mine as shown. This would seem to confirm the suspicion that this group of "shocks" are associated with the mines.

It is planned to plot all future earthquakes on a similar map, and if activity continues, it is to be expected that the areas of major activity will soon be well established.

Dominion Astrophysical Observatory
Victoria, B.C.
July, 1952

CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
DOMINION OBSERVATORIES

PUBLICATIONS

OF THE

Dominion Observatory

OTTAWA

VOL. XVI No. 4

Application of Gravimeter Observations to the Determination of the Mean Density of the Earth and of Rock Densities in Mines

BY

A. H. MILLER and M. J. S. INNES

EDMOND CLOUTIER, C.M.G., O.A., D.S.P.
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
OTTAWA, 1953

APPLICATION OF GRAVIMETER OBSERVATIONS TO THE DETERMINATION OF THE MEAN DENSITY OF THE EARTH AND OF ROCK DENSITIES IN MINES

By A. H. Miller and M. J. S. Innes

INTRODUCTION

Subterranean observations of gravity are of value for two reasons:

(1) As first shown by Airy[1] from pendulum measurements at the top and bottom of Harton Colliery, they may be used to determine the mean density of the earth from the following equation which he derived:

$$\frac{\rho}{\bar{\rho}} = \frac{r}{3\Delta r} \cdot \frac{g_a}{g_b} - \left[\frac{r}{3\Delta r} - \frac{2}{3}\right] \dots\dots\dots\dots (1)$$

where Δr is the thickness of the spherical shell corresponding to the depth of the mine and ρ the corresponding density. The radius of the earth is represented by r, while g_a and g_b are gravity at the top and bottom of the mine respectively, and $\bar{\rho}$ is the mean density of the earth.

(2) Such observations may also be employed to determine the densities of rock layers beneath the surface, and it has been one of the objects of this paper to demonstrate, this application in connection with the results at Lake Shore and Noranda.

In Airy's experiment a pendulum and a pendulum clock were set up at the top of the mine, and a similar set was installed at the bottom of the mine. Six swings of four hours were made with the pendulums per day and compared with the respective clocks by the method of coincidences. The observations lasted from October 2 to October 21, 1854. The pendulums were interchanged between bottom and top of the mine three times on October 9, 16 and 19, following the initial set-up on October 2. Eighty-two swings were made between October 2 and October 21. Eight observers were employed, representing, in addition to the Royal Observatory, Oxford, Cambridge, and Durham observatories. Every assistance was given by Mr. William Anderson, principal owner of the mine. Mr. G. W. Arkley, local viewer and superintendent of the mine works, assisted with some of the required measurements and "furnished a complete account of the strata passed through in sinking the Harton shaft with specimens of a great number of rocks. These were submitted to Professor W. H. Miller, who, with great labour, determined their specific gravities". Airy gives a table which lists the thicknesses of the

---

[1] Account of Pendulum Experiments undertaken in the Harton Colliery, for the purpose of determining the mean density of the earth, by G. B. Airy, Esq., Astronomer Royal, Phil. Trans. Roy. Soc. London, Vol. 146, 1856, pp. 297-352, with an addendum by Professor Stokes, pp. 353-355.

142 strata composing the mine section with the corresponding specific gravities and summarizes them into 1,211 feet of rocky and shaly beds of specific gravity 2·56, 30 feet of coaly beds of specific gravity 1·43, 15 feet completely worked out and, from these, found the mean specific gravity to be 2·50. Employing this in his formula for the mean density of the earth, he obtained for that quantity the value 6·566 ± 0·182. In order to correct for irregularities of the terrain in the vicinity of the mine, a map showing elevations for a distance of three miles was prepared. The effect of the ellipticity and rotation of the earth forms the subject matter for the addendum by Stokes who showed that, for the latitude of the Colliery, the corrections for these would only alter Airy's value by one unit in the third place of decimals, or from 6·566 to 6·565. Everything in connection with this interesting experiment, including the preparation of an equally valuable paper, was carried out with such meticulous attention to detail that it is at first sight rather amazing that the result should differ so much from the generally accepted value, now, of 5·52[1].

Possibly the explanation lies in the difficulty of determining the precise gravitational effect of rock formations from measurement of the corresponding densities. In a recent article Sigmund Hammer[2] remarks: "It is clear that sample measurements have so large a scatter that prohibitively many measurements would be required to form a representative average density log over sufficiently large intervals. It is also evident that the attempts to recover initial conditions by soaking and vacuum saturating (under atmospheric pressure) the samples were completely futile. We are convinced that sample measurements on shales of this type are on the one hand prohibitively laborious and, on the other hand, practically valueless for the purpose of constructing a density log of the actual rocks as they exist underground."

LOCATIONS AND DEPTHS OF SHAFTS AT LAKE SHORE AND NORANDA AND TABULATION OF THE GRAVIMETER RESULTS

Relative locations of shafts 4, 5, and 6 at Lake Shore are shown in Figure 1, and those of shafts 3, 4, 5, and 6 at Noranda in Figure 2; Figure 3 shows the relative depths of the shafts of both mines. The essential data are tabulated principally in columns 1 to 4 of Tables 1 to 7. The corresponding deduced gravity gradients and densities are given in the following two columns. The gradients are all negative although they are not so indicated in the tables. They correspond to an increase of gravity with depth.

It will be noticed in the tabulations that the gravity gradients in the uppermost section at the surface are always the largest. This may be due to the fact that any irregularities in the terrain above or below the uppermost gravimeter stations have the effect of decreasing gravity at the uppermost station. As the area is partially drift covered, and therefore overlain by masses of lower density, this may also contribute to the result.

---

[1] Smithsonian Physical Tables, p. 75, Eighth Revised Edition, 1933.

[2] Density Determinations by Underground Gravity Measurements, Geophysics XV, No. 4, pp. 637-652, October, 1950.

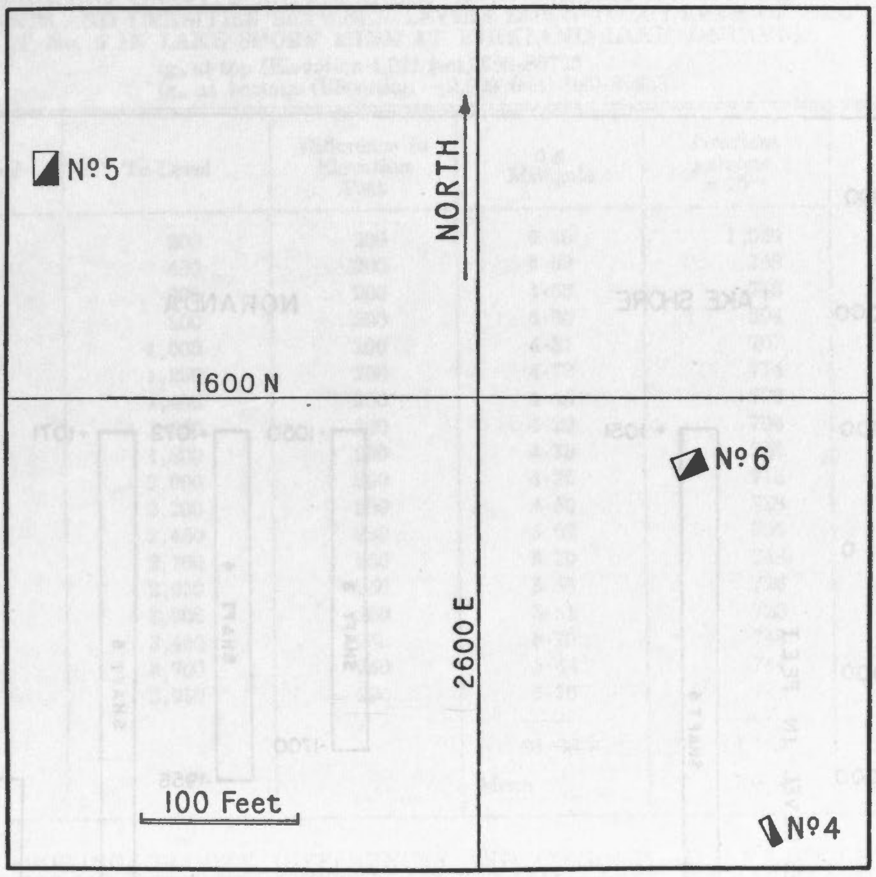


FIGURE 1—Showing location of shafts at Lake Shore.

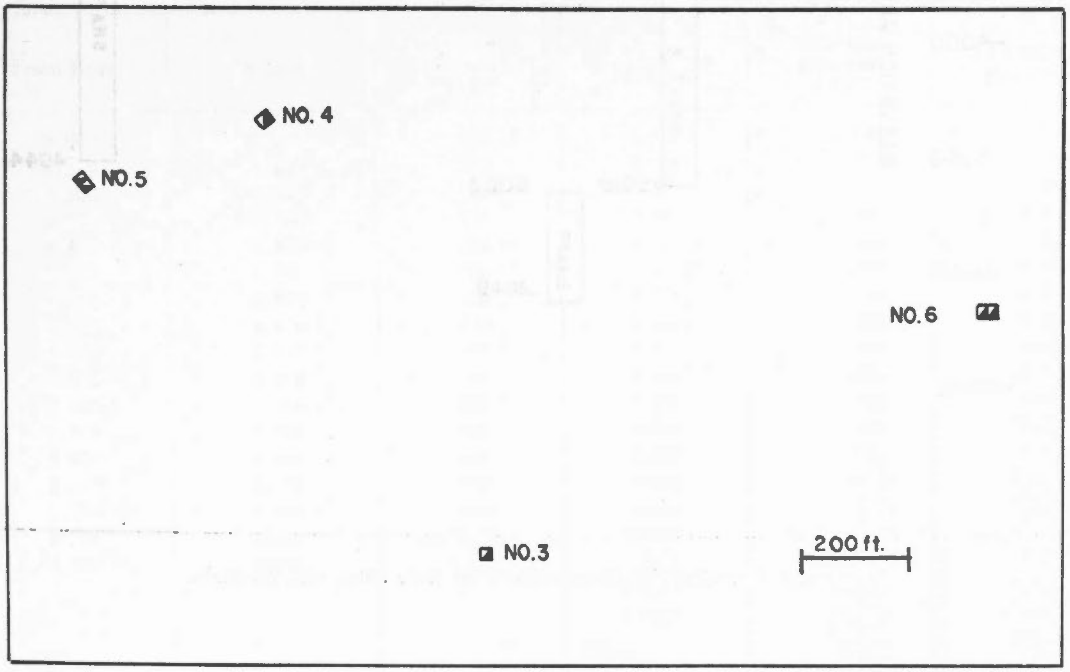


FIGURE 2—Showing location of shafts at Noranda.

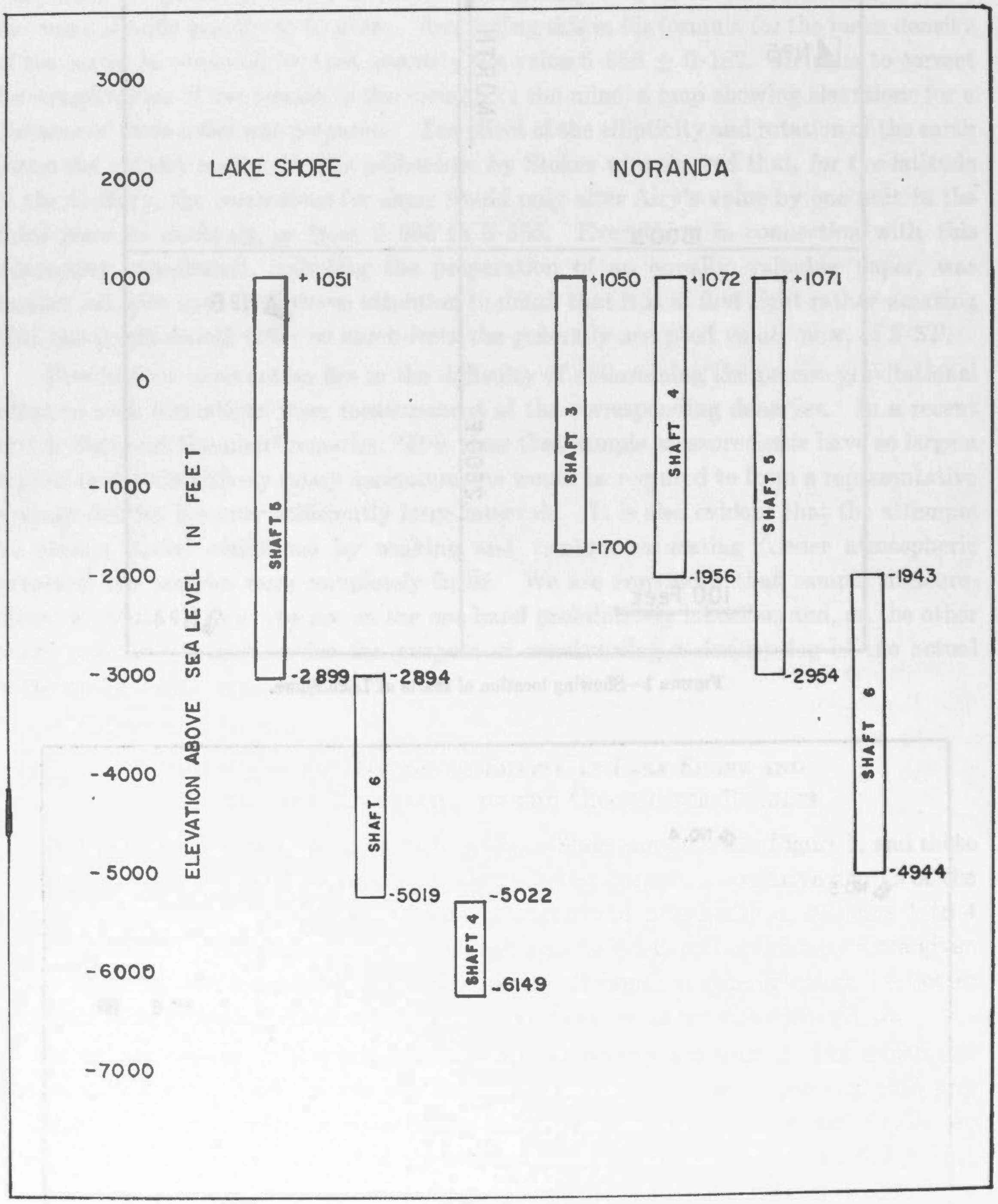


FIGURE 3—Showing elevations of shafts at Lake Shore and Noranda.

TABLE 1.—SHOWING GRAVITY DIFFERENCES AND CORRESPONDING DEDUCED GRAVITY GRADIENTS AND DENSITIES BETWEEN LEVELS DOWN TO A DEPTH OF 3,950 FEET IN SHAFT No. 5 IN LAKE SHORE MINE AT KIRKLAND LAKE, ONTARIO.

(g_o at top (Elevation 1,051 feet) 980·80725
(g_o at bottom (Elevation −2,899 feet) 980·89833

From Level	To Level	Difference in Elevation Feet	Δ g Milligals	Gradient gals/cm. x 10^{-9}	Density gms./cc.
0	200	200	6·40	1,050	2·427
200	400	200	4·62	758	2·775
400	600	200	4·53	743	2·793
600	800	200	4·90	804	2·720
800	1,000	200	4·31	707	2·836
1,000	1,200	200	4·72	774	2·756
1,200	1,400	200	4·45	730	2·809
1,400	1,600	200	4·29	704	2·840
1,600	1,800	200	4·79	786	2·742
1,800	2,000	200	4·36	715	2·827
2,000	2,200	200	4·50	738	2·799
2,200	2,450	250	5.63	739	2·798
2,450	2,700	250	5·70	748	2·787
2,700	2,950	250	5·53	726	2·813
2,950	3,200	250	5·51	723	2·817
3,200	3,450	250	5·70	748	2·787
3,450	3,700	250	5·44	714	2·828
3,700	3,950	250	5·70	748	2·787
			91·08	13,655	49·941
			Mean	758·6	2·775

TABLE 2.—SHOWING GRAVITY DIFFERENCES AND CORRESPONDING DEDUCED GRAVITY GRADIENTS AND DENSITIES BETWEEN LEVELS 3,950 and 6,075 FEET IN SHAFT No. 6 IN LAKE SHORE MINE AT KIRKLAND LAKE, ONTARIO.

(g_o at top (Elevation −2,894 feet) 980·89779
(g_o at bottom (Elevation −5,019 feet) 980·94539

From Level	To Level	Difference in Elevation Feet	Δ g Milligals	Gradient gals/cm. x 10^{-9}	Density gms./cc.
3,950	4,075	125	2.65	696	2·849
4,075	4,200	125	2·79	732	2·806
4,200	4,325	125	2·81	738	2·799
4,325	4,450	125	2·91	764	2·768
4,450	4,575	125	2·61	685	2·862
4,575	4,700	125	2·83	743	2·793
4,700	4,825	125	2·72	714	2·828
4,825	4,950	125	2·93	769	2·762
4,950	5,075	125	2·77	727	2·812
5,075	5,200	125	2·63	690	2·856
5,200	5,325	125	2·84	745	2·791
5,325	5,450	125	2·94	772	2·758
5,450	5,575	125	2·94	772	2·758
5,575	5,700	125	2·60	682	2·866
5,700	5,825	125	2·84	745	2·791
5,825	5,950	125	2·84	745	2·791
5,950	6,075	125	2·95	774	2·756
			47·60	12,493	47·646
			Mean	734·9	2·803

TABLE 3.—SHOWING GRAVITY DIFFERENCES AND CORRESPONDING DEDUCED GRAVITY GRADIENTS AND DENSITIES BETWEEN LEVELS 6,075 and 7,200 FEET IN LAKE SHORE MINE AT KIRKLAND LAKE, ONTARIO.

(g_o at top (Elevation −5,022 feet) 980·94502
(g_o at bottom (Elevation −6,149 feet) 980·97016

From Level	To Level	Difference in Elevation Feet	Δ g Milligals	Gradient gals/cm. x 10^{-9}	Density gms./cc.
6,075	6,325	250	5·51	732	2·817
6,325	6,575	250	5·81	762	2·770
6,575	6,825	250	5·42	711	2·831
6,825	7,200	375	8·40	735	2·803
			25·14	2,940	11·221
			Mean	735	2·805

TABLE 4.—SHOWING GRAVITY DIFFERENCES AND CORRESPONDING DEDUCED GRAVITY GRADIENTS AND DENSITIES BETWEEN LEVELS DOWN TO A DEPTH OF 2,750 FEET IN SHAFT No. 3 IN THE HORNE MINE OF NORANDA MINES LIMITED AT NORANDA, QUEBEC.

(g_o at top (Elevation 1,050·4 feet) 980·82080 gals
(g_o at bottom (Elevation −1,700·2 feet) 980·88442 gals

From Level	To Level	Difference in Elevation Feet	Δ g Milligals	Gradient gals/cm. x 10^{-9}	Density gms./cc.
0	123·1	123·1	4·17	1,111	2·354
123·1	222·8	99·7	2·35	773	2·757
222·8	324·4	101·6	2·32	749	2·786
324·4	424·8	100·4	2·44	797	2·729
424·8	524·0	99·2	2·56	847	2·669
524·0	625·7	101·7	1·99	642	2·914
625·7	745·1	119·4	2·86	786	2·742
745·1	873·7	128·6	3·17	809	2·714
873·7	998·9	125·2	3·02	791	2·736
998·9	1,123·8	124·9	2·96	778	2·751
1,123·8	1,244·4	120·6	3·07	835	2·683
1,244·4	1,373·9	129·5	2·98	755	2·779
1,373·9	1,495·3	121·4	3·37	911	2·593
1,495·3	1,623·5	128·2	3·38	865	2·647
1,623·5	1,748·4	124·9	2·27	596	2·969
1,748·4	1,873·8	125·4	2·37	620	2·940
1,873·8	1,998·6	124·8	2·65	697	2·848
1,998·6	2,124·4	125·6	2·65	692	2·854
2,124·2	2,249·1	124·9	2·96	778	2·751
2,249·1	2,374·0	124·9	2·69	707	2·836
2,374·0	2,499·0	125·0	1·93	507	3·075
2,499·0	2,750·5	251·5	5·46	712	2·830
			63·62	16,758	60·957
			Mean	761·7	2·771

TABLE 5.—SHOWING GRAVITY DIFFERENCES AND CORRESPONDING GRAVITY GRADIENTS AND DENSITIES BETWEEN LEVELS DOWN TO A DEPTH OF 3,028 FEET IN SHAFT No. 4 IN THE HORNE MINE AT NORANDA, QUEBEC

(g_o at top (Elevation 1,072·3 feet) 980·81853 gals

(g_o at bottom (Elevation −1,955·6 feet) 980·89066 gals

From Level	To Level	Difference in Elevation Feet	Δ g Milligals	Gradient gals/cm. x 10^{-9}	Density gms./cc.
0	137·6	137·6	4.88	1,164	2·291
137·6	342·0	204·4	5·18	831	2·688
342·0	543·1	201·1	5·04	822	2·699
543·1	768·3	225·2	5·42	790	2·737
768·3	1,021·9	253·6	5·77	746	2·790
1,021·9	1,147·0	125·1	2·86	750	2·785
1,147·0	1,271·2	124·2	3·05	806	2·718
1,271·2	1,397·0	125·8	2·79	728	2·811
1,397·0	1,522·0	125·0	2·81	738	2·799
1,522·0	1,650·6	128·6	2·93	747	2·788
1,650·6	1,772·0	121·4	2·89	781	2·748
1,772·0	1,901·4	129·4	2·86	725	2·815
1,901·4	2,023·8	122·4	2·88	772	2·758
2,023·8	2,151·9	128·1	2·82	722	2·818
2,151·9	2,277·1	125·2	3·33	873	2·638
2,277·1	2,402·2	125·1	2·43	637	2·920
2,402·2	2,527·8	125·6	2·82	737	2·800
2,527·8	2,651·6	123·8	2·77	734	2·804
2,651·6	2,777·7	126·1	2·88	749	2·786
2,777·7	2,901·6	123·9	2.70	715	2·827
2,901·6	3,027·9	126·3	3·02	784	2·744
			72·13	16,351	57·764
			Mean	778·6	2·751

TABLE 6.—SHOWING GRAVITY DIFFERENCES AND CORRESPONDING GRAVITY GRADIENTS AND DENSITIES DOWN TO A DEPTH OF 4,025 FEET IN SHAFT No. 5 IN THE HORNE MINE AT NORANDA, QUEBEC.

(g_o at top (Elevation 1,070·8 feet) 980·81865 gals

(g_o at bottom (Elevation −2,954·0 feet) 980·91313 gals

From Level	To Level	Difference in Elevation Feet	Δ g Milligals	Gradient gals/cm. x 10^{-9}	Density gms./cc.
0	133·9	133·9	4·38	1,073	2·399
133·9	338·1	204·2	5·42	871	2·640
338·1	762·8	424·7	10·58	817	2·705
762·8	1,016·9	254·1	5·46	705	2·838
1,016·9	1,269·4	252·5	6·26	813	2·710
1,269·4	1,518·7	249·3	5·63	741	2·795
1,518·7	1,769·0	250·3	6·12	802	2·723
1,769·0	2,019·5	250·5	5·39	706	2·837
2,019·5	2,272·9	253·4	6·01	778	2·751
2,272·9	2,525·2	252·3	5·58	726	2·813
2,525·2	2,773·6	248·4	5·79	765	2·767
2,773·6	3,023·9	250·3	5·42	710	2·833
3,023·9	3,273·9	250·0	5·93	778	2·751
3,273·9	3,523·3	249·4	5·60	737	2·800
3,523·3	3,774·2	250·9	5·56	727	2·812
3,774.2	4,024·7	250·5	5·35	701	2·843
			94·48	12,450	44·017
			Mean	778·1	2·751

TABLE 7.—SHOWING GRAVITY DIFFERENCES AND CORRESPONDING GRAVITY GRADIENTS AND DENSITIES FROM THE TOP OF THE SHAFT No. 6 DOWN TO A DEPTH OF 3,001 FEET IN THE SHAFT CORRESPONDING TO A DEPTH OF 7,026 FEET BELOW THE TOP OF SHAFT No. 5 IN HORNE MINE AT NORANDA, QUEBEC.

(g_o at top (Elevation −1,943·2 feet) 980·89078 gals
(g_o at bottom (Elevation −4,943·9 feet) 980·95848 gals

From Level	To Level	Difference in Elevation Feet	Δ g Milligals	Gradient gals/cm. x 10^{-9}	Density gms./cc.
3,014·9	3,513·5	499·5	10·83	711	2·832
3,513·5	3,762·8	249·3	5·70	750	2·785
3,762·8	4,013·7	250·9	5·49	718	2·823
4,013·7	4,264·5	250·8	5·39	705	2·838
4,264·5	4,514·5	250·0	6·10	801	2·724
4,514·5	4,764·5	250·0	5·60	735	2·803
4,764·5	5,014·7	250·2	5·84	766	2·766
5,014·7	5,264·7	250·0	5·63	739	2·798
5,264·7	5,514·7	250·0	5·82	764	2·768
5,514·7	6,014·7	500·0	11·30	741	2·795
			67·70	7,430	27·932
			Mean	743	2·793

Application of Airy's Method to Lake Shore and Noranda

The accuracy of Airy's method to determine the mean density of the earth depends primarily[1] upon the accuracy of the gravity measurements and of the value to be used for the mean density of the rocks lying between the upper and lower gravity stations. If $\bar{\rho}$ is to be determined with an error not exceeding $\frac{1}{500}$th part of the whole, g_a, g_b must be known to one part in a million or to 1 milligal, while the error in ρ must not exceed 0·005 gms. per cc.

The errors in the gravity measurement for Lake Shore and Noranda are considered to be less than $\frac{1}{10}$ milligal and therefore would not affect the results within the desired limits of accuracy. On the other hand no direct determinations of density by weighing were made by the authors either at Lake Shore or Noranda. The most plausible density available seemed to be that obtained by Garland for thirteen listed groups of Precambrian rocks[2] and equals 2·794 gms. per cc. When this value of ρ is substituted in Airy's formula, and if the values of gravity obtained by Innes at the top of shaft 5 and the bottom of shaft 4 at Lake Shore (a depth of 7,200 feet corresponding to Δr) are used for g_a and g_b, there is obtained

$$\frac{\rho}{\bar{\rho}} = 0\cdot506 \text{ or } \bar{\rho} = 5\cdot52 \text{ gms. per cc.}$$

---

[1] The results are insensitive to large error in the value adopted for r, the radius of the earth, while Δr the depth of the mine is ascertained by direct measurement.

[2] Publications of the Dominion Observatory, XVI, No. 1, p. 48.

Similar application of the results obtained for shafts 4 and 5 of Noranda mine (a depth of 6,016 feet) gives

$$\frac{\rho}{\bar{\rho}} = 0\cdot502 \text{ or } \bar{\rho} = 5\cdot57 \text{ gms. per cc.}$$

These results are within one per cent of the accepted[1] value of the mean density of the earth, and are as good as one would expect considering the uncertainty of the value used for ρ.

THE VERTICAL GRADIENT AND THE MEAN DENSITY OF THE EARTH

The formula[2] for the vertical gradient of gravity in a sphere is given by

$$\frac{dg}{a\,r} = 4\,\pi\,G\left[\rho - \frac{2}{3}\bar{\rho}\right]\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

where $\frac{dg}{ar}$ is the gradient, G is the gravitational constant, ρ is the density at radius r, and $\bar{\rho}$ is the mean density of the earth regarded as spherical and without rotation. Before applying the observations (obtained on the earth which is rotating) it is of interest to make an estimate of the effect of the ellipticity and rotation of the actual earth which approaches the form of that of a spheroid. The matter has previously been investigated by Stokes in connection with Airy's observations.

Stokes developed the following equation[3] for the vertical gradient of gravity neglecting squares and higher powers of ϵ and m:

$$-\frac{1}{g}\frac{dg}{dr} = \frac{2}{r}\,(\,1 - 2\,\epsilon\cos^2\,\theta + \epsilon + m\,)\ldots\ldots\ldots\ldots(3)$$

where θ is the co-latitude, ϵ is the ellipticity and m is the ratio of the centrifugal force to gravity at the equator, equal respectively to $\frac{1}{297}$ and $\frac{1}{288\cdot36}$ for the international spheroid.

---

[1] The generally accepted value of $\bar{\rho}$ is 5·52 (Smithsonian Physical Tables, p. 75, Eighth Revised Edition, 1933), while the international formula for gravity implies a mean density for the spheroid of 5·5124 gm./cm.^{3} (Gravity Anomalies and the Figure of the Earth, Professional Paper No. 30, Survey of India, 1940, p. 34, by B. L. Gulatee).

[2] Note on the Variation of Gravity with Depth, by A. E. Benfield, Zeitscrift fur Geophysik, Vol. XIII, p. 157, 1937. Gravity in the Interior of the Earth, by R. Meldrum Stewart, Contributions from the Dominion Observatory, Vol. I, No. 4, 1950.

For a spherical earth of radius r and mean density $\bar{\rho}$, gravity on it is given by

$$g_b = \frac{4}{3}\pi\,G\,r\,\bar{\rho}\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(i)}$$

If surrounded by a spherical shell of radius r+Δr and of density ρ, neglecting second order terms, gravity at the surface will be

$$g_b = \frac{4}{3}\pi\,G\,r\,\bar{\rho}\left[1 - 2\frac{\Delta r}{r} + 3\frac{\Delta r}{r}\frac{\rho}{\bar{\rho}}\right]\ldots\ldots\ldots\ldots\text{(ii)}$$

Airy's formula (1) and the formula for the vertical gradient (2) are obtained by division and subtraction respectively of these two equations.

It is also of interest to note that the formula frequently employed for reduction of subsurface observations of gravity is equivalent to equation (2); namely

$$-\Delta g = \text{Free Air Correction} - 2 \text{ x Bouguer Correction for an infinite slab}$$

$$= \left(2 \text{ x } \frac{4}{3}\pi\,G\bar{\rho} - 4\,\pi\,G\,\rho\right)\Delta r$$

$$\text{or}\quad \frac{\Delta g}{\Delta r} = 4\,\pi\,G\left(\rho - \frac{2}{3}\bar{\rho}\right)$$

[3] This equation reduces to equation (2) on the assumption of ϵ and m = 0, as is the case for a sphere without rotation, and assuming also that ρ = 0, as it is effectively on the surface of the earth.

TABLE 8.

(1)	(2) Depth	(3) Δ g (Observed) (gals)	(4) Centrifugal Effect (gals)	(5) Δ g (Corrected) (gals)	(6) $\frac{dg}{dr}$ (gals per cm. x 10^9)	(7) $\bar{\rho}$ (gm./cm.^{3})	(8) G x 10^9	(9) ρ (gm./cm.^{3})
1. Lake Shore Mine Shafts No. 4, 5	Surface to 7,200 ft.	0·16291	0·00052	0·16239	739·97	5·516	66·46	2·797
2. Noranda Mine Shafts No. 4, 6	Surface to 6,016·2 ft.	0·13995	0·00043	0·13952	760·87	5·553	68·34	2·772
3. Lake Shore Mine Shaft No. 5	200 ft. to 3,950 ft.	0·08468	0·00027	0·08441	738·50	5·513	66·33	2·799
4. Noranda Mine Shaft No. 5	133·9 ft. to 4,027·7 ft.	0·09010	0·00028	0·08982	757·740	5·547	68·03	2·776

This equation shows that in relation to unity the combined effects of ellipticity and rotation are at the equator $\epsilon + m$, at latitude 45° m, and at the pole $-\epsilon + m$. The effect on the gradient at latitude 45° is thus entirely that due to centrifugal force. At Kirkland Lake and approximately also at Noranda $\cos^2\theta = 0{\cdot}5549$, so that $-2\epsilon\cos^2\theta + \epsilon + m = -0{\cdot}111\,\epsilon + m$, and the combined effect of ellipticity and rotation is largely due to centrifugal force at that latitude also. This combined effect corresponds to somewhat more than one part in 300 of the total gradient.

The Centrifugal force at latitude φ resolved in the direction of the vertical is $r\,w^2\cos^2\varphi$ and at a depth h is $(r-h)\,w^2\cos^2\varphi$, where r is the radius of the earth and w the angular velocity. Between the surface and a point in the interior the difference is $h\,w^2\cos^2\varphi$. For the latitude of Kirkland Lake and Noranda, 48°09·0 and 48°14·9 respectively, the values of $h\,w^2\cos^2\varphi$ are $0{\cdot}721 \times 10^{-4}$ and $0{\cdot}719 \times 10^{-4}$ in units of cm. per sec.^{2} for h equal to 1,000 feet.

The total centrifugal effect in the observed gravity difference between upper and lower stations is tabulated in column (4) of Table 8. It amounts to $5{\cdot}2 \times 10^{-4}$ and $4{\cdot}3 \times 10^{-4}$ cm. per sec.^{2} for Lake Shore mine and Noranda mine respectively. Column 5 gives the gravity difference and column 6, the gradient of gravity corrected for rotation. The gradients have been employed using formula (2) to derive a value for each of the quantities ρ, G, and ρ, in turn, on the assumption of the accepted values of the other two. The results are given in columns 7, 8 and 9 of Table 8.

The values obtained for ρ, the mean density of the earth, do not differ significantly from those obtained using Airy's method which does not involve assumption of the value[1] of the gravitational constant.

As objection may be reasonably raised to determination of gradients from observations of gravity which do not lie on the same vertical, lines 3 and 4 of Table 8 were prepared from observations taken in shaft 5 at Lake Shore and the same numbered shaft at Noranda. The results differ slightly but not significantly from those previously obtained for the respective mines (lines 1 and 2, Table 8).

In order to eliminate the apparently anomalous gradient usually observed at the top levels, the gradients for these shafts have been computed from the second level to the bases of the shafts.

Column 9, Table 8, shows that the assumed mean value for the density of the rocks (2·794) fits Lake Shore mine as well as might reasonably be expected, but that this value is somewhat too large for Noranda. However, even for Noranda the difference between the previously assumed value and that computed from the observations is only 0·02 from Garland's mean value for Precambrian rocks of the district, namely 2·794.

---

[1] Heyl gives $66{\cdot}64 \times 10^{9}$ for G in his paper "A Redetermination of the Newtonian Constant of Gravitation", Proc. Nat. Acad. of Sciences, pp. 601-605, Vol. 13, 1927. The value $66{\cdot}7 \times 10^{-9}$ has usually been employed by the writers as it has frequently been adopted by others and is convenient in computation, being nearly equivalent to

$$\frac{200}{3} \times 10^{-9}$$

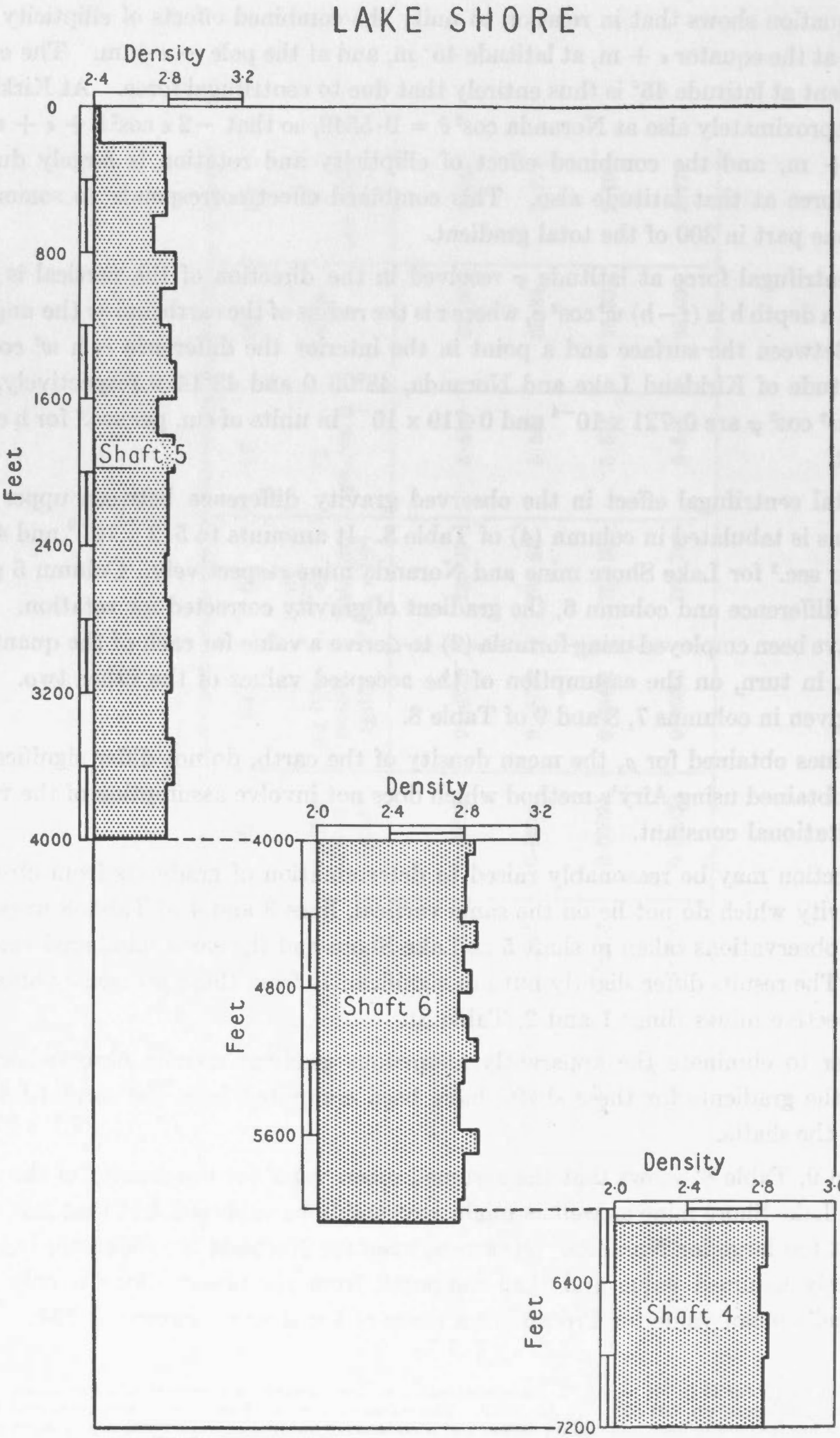


FIGURE 4—Showing density profiles for shafts 5, 6, and 4 at Lake Shore.

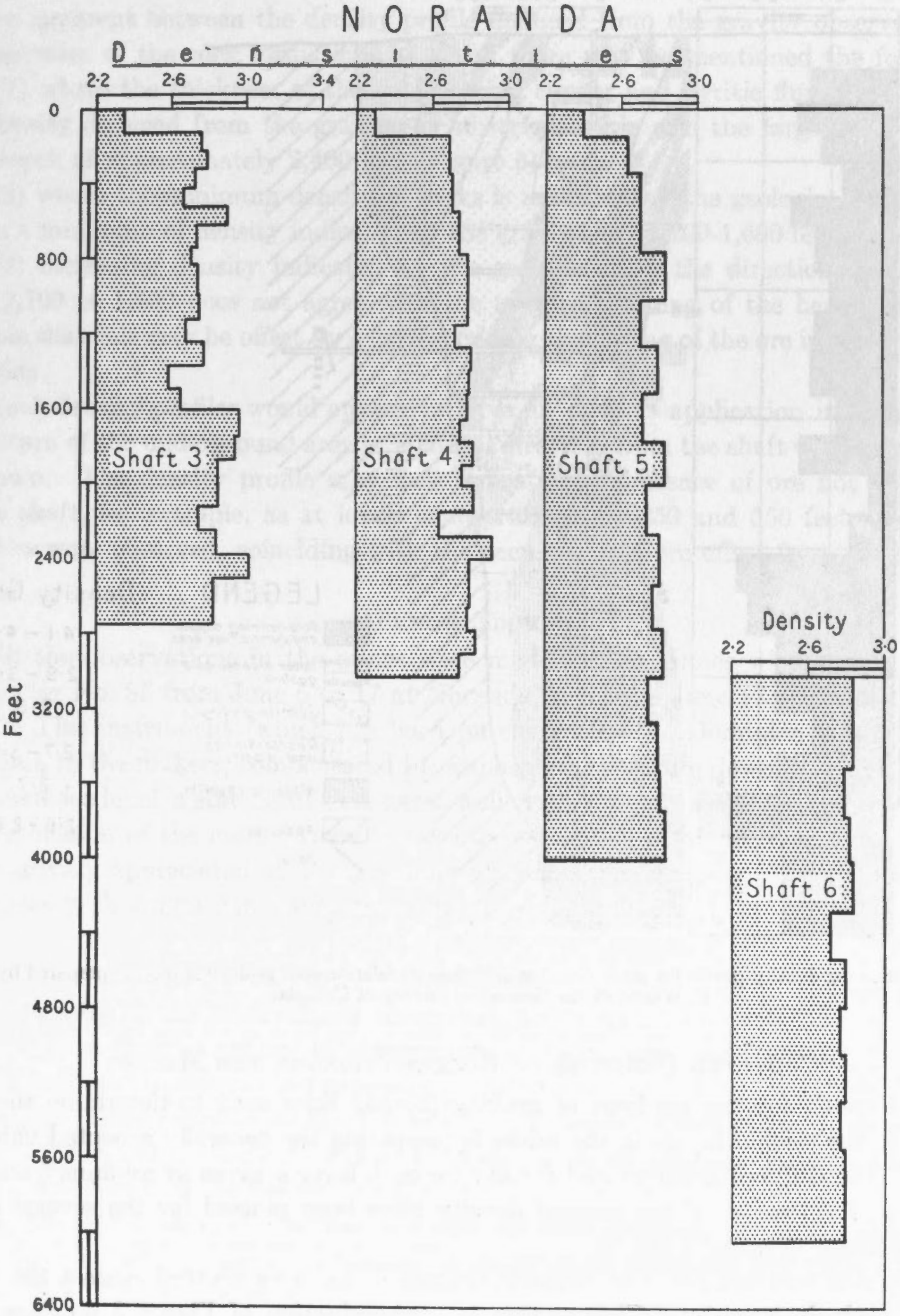


FIGURE 5—Showing density profiles for shafts 3, 4, 5, and 6 at Noranda.

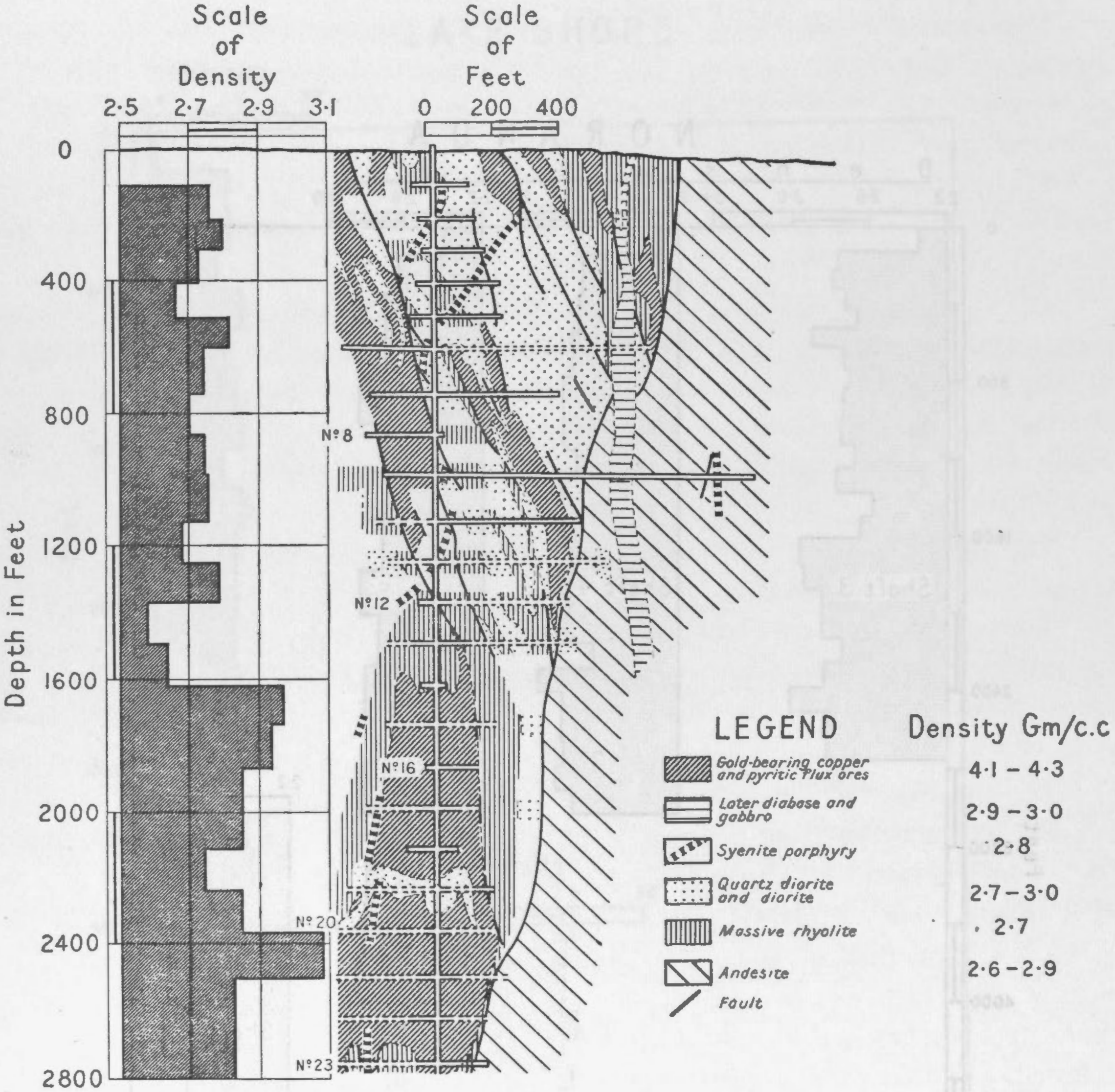


FIGURE 6—Showing density profile for shaft No. 3 at Noranda in relation to a geological section prepared by Dr. M E. Wilson of the Geological Survey of Canada.

COMPUTED DENSITIES OF ROCK SECTIONS IN THE MINES

The formula for the gradient of gravity (2) has been used to determine the rock densities of the several layers in the mines by assuming the generally accepted values of G and ρ. The deduced gradient and density for each layer is given in columns 5 and 6 of Tables 1 to 7. Profiles of the derived density have been plotted for the several shafts in the two mines (Figures 4 and 5).

The profile for shaft No. 3 at Noranda (Figure 6) has been plotted against the corresponding geological section. This section is a reproduction of Figure 3 on Page 62 of Geological Survey Memoir 229 by M. E. Wilson, 1941. Densities of the rocks listed in the legend have been added by the authors of this paper and were taken chiefly from values given by Heiland[1].

---

[1] Geophysical Exploration, C. A. Heiland, 1940.

A considerable amount of ore has been removed from the mine and it is possible that the distribution of the stopes could be such as to invalidate any comparison between the deduced densities and the geological section. Certain obvious relations are nevertheless apparent between the density profile deduced from the gravity observations and the densities of the rock formations of which there may be mentioned the following:

(1) where the thickness of the gold-bearing copper and pyritic flux ores is greatest, the density deduced from the gravimeter observations is also the largest. This occurs at a depth of approximately 2,400 feet (Figure 6);

(2) where the minimum density of rocks is indicated by the geological section, there is also a minimum of density indicated by the gravimeter (1,200-1,600 feet) in the profile;

(3) increasing density indicated by the gravimeter in the direction upwards from level 2,100 to 1,600 does not agree with the upward thinning of the heavy ore*. It is possible that this may be offset by a corresponding thickening of the ore in a perpendicular direction.

Such density profiles would appear to have an obvious application in a shaft where the nature of the underground area in a lateral direction from the shaft was comparatively unknown. The density profile may well indicate the presence of ore not encountered in the shaft, for example, as at levels of approximately 250 and 550 feet where larger densities were observed, coinciding with the occurrence of ore offset from the shaft.

ACKNOWLEDGMENT

All the observations in the mines were made by Mr. Innes with North American gravimeter No. 85 from June 5 to 17 at Noranda, and from June 17 to 22, 1948 at Lake Shore. This instrument (which has been purchased by the Dominion Observatory) is, according to the makers, compensated for atmospheric pressure down to a depth of 6,000 feet below sea level, a statement that seems well verified by the results of the observations.

Permission of the mine owners to take the observations rendered this work possible and is greatly appreciated as is the willing assistance rendered by all mine officials and employees with whom Mr. Innes came in contact.

CONCLUSION

1. Results of the observations show that Airy's method of determining the mean density of the earth as applied to observations at Lake Shore and Noranda yields values that are reasonably close to the generally accepted value of 5·52.

2. The density profile deduced from the gravimeter observations at Noranda, for which a geological section was available, shows a direct relation between the density and the occurrence of the ore.

3. The results also indicate that, in a mine not fully explored, gravimeter observations would be of value in giving an indication of the levels at which ore was most likely to be found.

---

* Since the above was written, samples of backfill employed in the mining operations have been supplied by the mining company. Measurement of several samples when saturated (as the backfill would no doubt be in the mine) gave a density of 2·47 gms. per cc. The backfill is therefore lighter than any of the rocks shown in Figure 6. Knowledge of this density would not appear to alter the validity of any statements made above. It may indicate, for example, that between the 14th and 19th levels proportionally increasing amount of backfill had been employed, that comparatively less backfill had been put in between the 20th and 21st level than between the 21st and 23rd.

CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
DOMINION OBSERVATORIES

PUBLICATIONS
OF THE
Dominion Observatory
OTTAWA

VOL. XVI No. 5

A SEISMIC SURVEY IN THE CANADIAN SHIELD
I: Refraction Studies Based on Rockbursts at Kirkland Lake, Ont.

BY
JOHN H. HODGSON

EDMOND CLOUTIER, C.M.G., O.A., D.S.P.
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
OTTAWA 1953

TABLE OF CONTENTS

TABLE OF CONTENTS—Concluded

A Seismic Survey in the Canadian Shield

I: Refraction Studies Based on Rockbursts at Kirkland Lake, Ontario*

ABSTRACT

Between 1938 and 1943 a number of large rockbursts at Kirkland Lake were recorded at permanent seismological observatories in eastern Canada and in New England. Analysis of these records suggested that rockbursts enjoy certain unique advantages as an energy source in crustal studies, since they are susceptible of precise location and timing and yet have about the same energy distribution as earthquakes. Immediately after the war steps were taken to set out a refraction profile for detailed studies of the crust.

A seismograph was installed at Kirkland Lake to time the bursts at their source and 14 stations were occupied at distances varying from 8 to 174 km. The locations were occupied one or two at a time, the instruments being moved to new locations after bursts had been satisfactorily recorded. The stations were housed in portable prefabricated buildings especially designed for the purpose.

Several types of instruments were used during the life of the project, those finally selected being of a type designed by Willmore for use in South African crustal studies. Particular attention was given to accurate timing and it is shown that the elapsed time of a single event has an accuracy of the order of ± 0.06 seconds (p.e.).

The refraction profile obtained consists of the 14 field stations already mentioned plus 5 distant stations which recorded the earlier large bursts. First arrivals in the P and S groups suggest that the crust is single layered, and the point at which P_n is first observed provides confirmation of this conclusion. In the analysis of secondary arrivals it becomes necessary to conclude that the crust, by lateral variation in rock types and by variable thickness, provides several alternate paths for each ray, so that groups of phases are obtained rather than single distinct phases. Within these limits it is possible to account qualitatively for the secondary arrivals and to conclude that reflections are obtained from the base of the crust as the critical angle is approached and exceeded.

The records of the distant stations show a very large amplitude for about 10 sec. following the expected arrival time of the direct S waves. This group appears to be identical with that called L_g by Ewing and Press.

P and S velocities in the crustal layer are 6.246 ± 0.015 and 3.544 ± 0.023 km/sec., the uncertainties being probable errors. The P velocity below the Mohorovičić discontinuity is 7.913 ± 0.125 km/sec. if near-station data are used, and 8.176 ± 0.013 km/sec. combining data of near and distant stations. This suggests an increase of velocity with with depth. S_n velocity, based on the records of the distant stations only, is 4.85 ± 0.10 km/sec. The mean thickness of the crust, based on the P waves, is 35.4 ± 5.5 km., the uncertainty being the result of the uncertainties in the velocities, and not a true probable error. It is suggested that this uncertainty corresponds to the actual variation in crustal thickness.

INTRODUCTION

Between the years 1947 and 1951 the Dominion Observatory carried out a program aimed at determining the structure of the crust in the vicinity of Kirkland Lake, Ontario. This program should be regarded as the final stage of a larger study which had its beginning in 1938. At that time the first of a series of large rockbursts at Kirkland Lake was recorded on the seismographs at Ottawa. It was immediately recognized that a new source of seismic energy was available for crustal studies and that it enjoyed certain advantages over both earthquakes and blasts. The localized area in which the bursts occurred allowed a precision of timing and location comparable to that possible with blasts, while, on the other hand, the nature of energy release was similar to that of earthquakes. Steps were taken to install a seismograph at Kirkland Lake and, during the next several years, bursts timed at their source were recorded at Ottawa. This accumulation of records was analysed by

---

* A Thesis Submitted in Partial Fulfilment of the Requirements for the Degree of Doctor of Philosophy in the University of Toronto.

E. A. Hodgson[1], under whose direction they were obtained. One of the bursts was, in addition, recorded at Shawinigan Falls and at Weston, Mass. A refraction profile with three stations between 450 and 935 km. thus became available for analysis*. This was carried out by the present writer[2].

The difficulty of studying a profile that had its nearest station at such a great distance suggested that the further field work be done. The earlier station at Kirkland Lake having been abandoned, a new one was installed to time the bursts at their source and field stations were occupied at distances between 8 and 174 kms.

This paper will give a detailed description of the field work and will attempt to analyse the refraction profile provided by the two sets of records, those from the near stations and those from the distant ones obtained earlier.

During the course of the field work it became possible to time several large blasts at their source and to record them at the field stations and at Ottawa. The analysis of the blast records is reserved for the second paper of this series. In the third, and final, paper of the series the results of the work will be summarized in the form of trial travel-time curves appropriate to the Ottawa area.

THEORY

The basic theory of the methods employed in this work may be found in any good text-book of seismology. For the convenience of readers who are not seismologists, however, the following paragraphs explaining the terms and methods of refraction seismology, are included.

When a disturbance takes place in an elastic medium energy is transmitted throughout the body of that medium by waves of two types. The first is a wave of dilatation, designated P in seismology, the second a wave of rotation, designated S. These waves suffer reflection and refraction at boundaries, in accordance with Snell's Law, but with the complication that an incident wave of either type gives rise to reflected and refracted waves of both types. In general all the laws of geometrical optics may be applied to seismological problems provided this complication is borne in mind. In particular Fermat's Principle, that a ray will follow a path of minimum time, is particularly helpful in seismology.

In order to understand the principles of refraction seismology we shall begin with the very simple example, illustrated in Fig. 1, of a single uniform layer. The surface of the layer is the line AD_i, its base is the line BC_i, and both surfaces are supposed to be horizontal. Let the velocity of wave propagation in the surface layer be V_1, that in the underlying medium V_2 and let us suppose that V_2 is much greater than V_1.

Let us set off a charge of explosive at the point A and let us record the disturbance caused by the explosion at each of a number of seismograph stations D_1, D_2, etc., arranged in a straight line along the surface. For simplicity we shall assume that the disturbance caused by the explosion is purely irrotational so that we have only P waves to consider. Along what paths will the P energy reach the several seismograph stations? The most

---

[1] Hodgson, E. A.—"Velocity of Elastic Waves and Structure of the Crust in the Vicinity of Ottawa", *Bull. Seism. Soc. Am.* Vol. 32: 249–255, 1942.

* Records from Williamstown and Harvard have since been obtained.

[2] Hodgson, J. H.—"Analysis of Travel Times from Rockbursts at Kirkland Lake, Ontario", *Bull. Seism. Soc. Am.* Vol. 37: 5–17, 1947.

obvious path is the direct one which, because the velocity in the surface layer is uniform, is certainly a path of minimum time in the Fermat sense. The travel-time equation of this ray may be written immediately as

$$T_1 = \frac{\Delta}{V_1}$$

when Δ is taken as the variable of distance. This curve, a straight line through the origin, has been plotted in the upper part of the diagram.

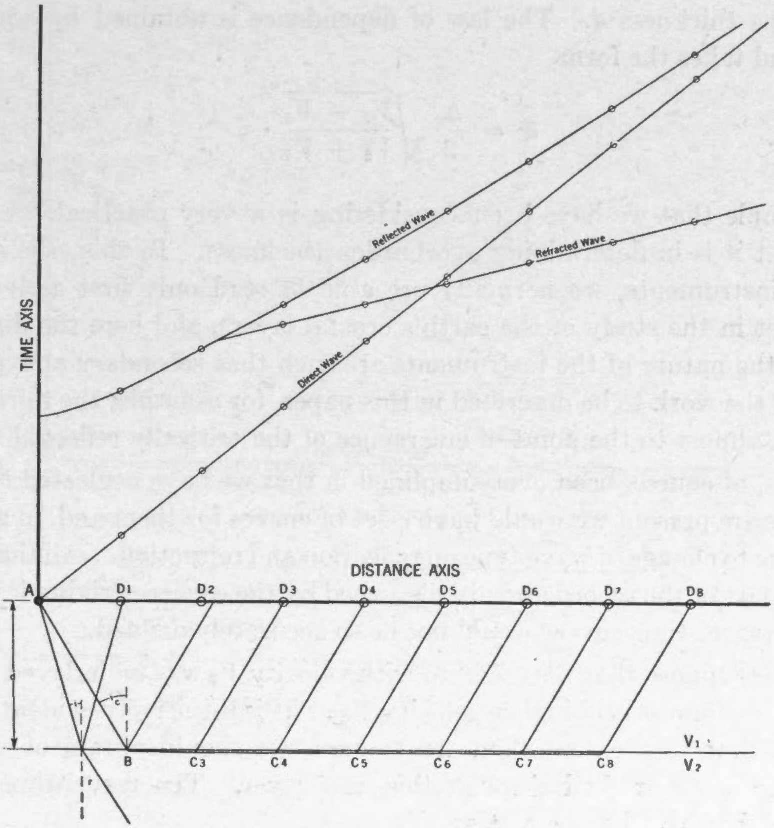


Figure 1—Ray paths (below) and travel-time curves (above) for single-layer crust.

A second phase which one would expect to find on the records is that corresponding to the rays reflected off the base of the layer. This phase should exist at all distances, and given the thickness d of the layer one could readily compute its travel-time curve as shown in the upper part of Fig. 1. However, we should note that the reflected phase must always be a secondary arrival and therefore, since seismograph records are usually confused after the beginning, it may be difficult to recognize the reflections on the records.

Not all the energy which strikes the base of the layer will be reflected. Part of it will be refracted into the underlying material, the angle r which the refracted ray makes with the normal being given by Snell's Law:

$$\frac{\sin i}{\sin r} = \frac{V_1}{V_2},$$

where i is the angle of incidence. If i assumes the critical angle i_0 so that r becomes 90°

then the refracted ray will travel along the interface and, upon being refracted upwards again, will reach the seismographs by paths of the form ABC_iD_i. The travel-times may readily be shown to obey the equation

$$T_2 = \frac{\Delta}{V_2} + \frac{2d \cos i_c}{V_1}.$$

This is a straight line whose slope is the inverse of the velocity V_2. It begins at the point where the critical reflected angle emerges and intersects the curve of T_1 at a point Δ_c which depends on the thickness d. The law of dependence is obtained by equating T_1 to T_2 for $\Delta = \Delta_c$ and takes the form

$$d = \frac{\Delta_c}{2}\sqrt{\frac{V_2 - V_1}{V_2 + V_1}}.$$

The example that we have been considering is a very practical one. One place in which we meet it is in determining overburden thickness. In this case, using the usual sort of field instruments, we normally are able to read only first arrivals. The same problem is met in the study of the earth's crustal layers, and here the dimensions of the problem and the nature of the instruments are such that secondary arrivals can often be detected. In the work to be described in this paper, for example, the refracted phase was detected back almost to the point of emergence of the critically reflected wave.

Fig. 1 has, of course, been over-simplified in that we have neglected the shear waves. If shear waves are present we would have a set of curves for them and, in addition, phases would exist due to change of wave type on reflection and refraction. All these phases would occur in that part of the record already disturbed by the earlier-arriving P waves. Consequently their travel-time curves would not be so accurately defined.

Now let us suppose that the medium with velocity V_2 was underlayed after a distance d_2 by another medium of still higher velocity V_3. It is intuitively evident that, if the line of seismograph stations extends out far enough, we should obtain observations corresponding to phases refracted through this new layer. The travel-time curve for this phase may be shown to have equation

$$T_3 = \frac{\Delta}{V_3} + \frac{2d_1 \cos i_{13}}{V_1} + \frac{2d_2 \cos i_{23}}{V_2}.$$

The ray paths and the travel-time curves of the refracted phases are shown in Fig. 2, (see following page.) which defines the angles given in the equation.

By comparing the travel-time equations for T_1, T_2, and T_3 the form for the general case becomes apparent, viz:

$$T_n = \frac{\Delta}{V_n} + \sum_{k=1}^{k=n-1} \frac{2d_k \cos i_{kn}}{V_k}$$

when d_k is the thickness of the k'th layer and i_{kn} is the angle made in the k'th layer by a ray which travels horizontally in the n'th layer.

On first thought it would appear that each of the n refracted phases would, for part of its course, appear as a first arrival. Actually this is not so, and unless a bed is thicker than a certain minimum thickness the phase refracted through it will appear throughout as a secondary arrival. It is difficult enough to trace secondary arrivals simply by extension of the curve from that part observed as first arrivals, but it is still more difficult to establish that a particular set of secondary arrivals indicate the presence of an additional bed. Under the circumstances depth calculations are likely to be in error.

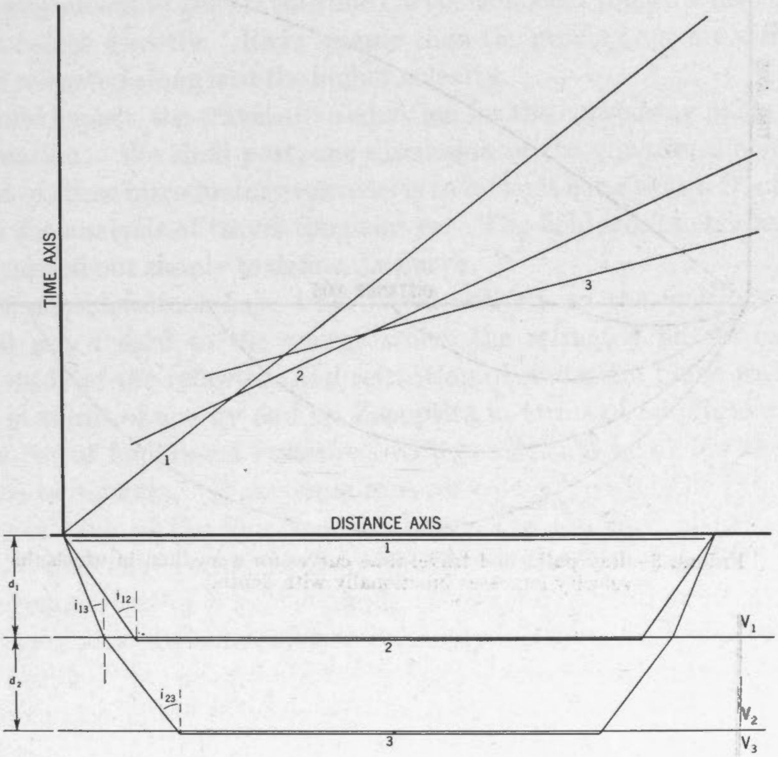


FIGURE 2—Ray paths and travel-time curves for a two-layer crust.

In all the foregoing remarks we have assumed that the velocity increased with each successively deeper bed. There is no reason, geologically, why this need be so. If a low-speed bed is present no refracted phase can be transmitted by it, for in accordance with Snell's Law the ray will be refracted toward the normal. The presence of low speed layers is likely to lead us into even more serious errors than the presence of thin beds for we have not even secondary arrivals to indicate their presence.

Still another of the complications of refraction studies arises from the presence of dipping beds. Up until now it has been assumed that all interfaces are horizontal. Dipping beds present a much less serious difficulty because they may be detected by firing a shot at each end of the spread of seismograph stations. If the velocities differ in the two directions it is an indication of dip, and the data provided by the reversed profile permit one to calculate true velocities, depths and dips.

It sometimes happens that a geologic section will have no discrete layers, but that the velocity increases with depth according to some functional relationship. In this case the ray path is curved, its depth of penetration being a function of the distance at which it emerges. The travel-time curve becomes a smooth curve as shown in Fig. 3. Under ordinary circumstances the travel-time curve carries in itself all the information necessary for the solution of the problem, and depth penetration and the velocity-depth distribution can be determined.

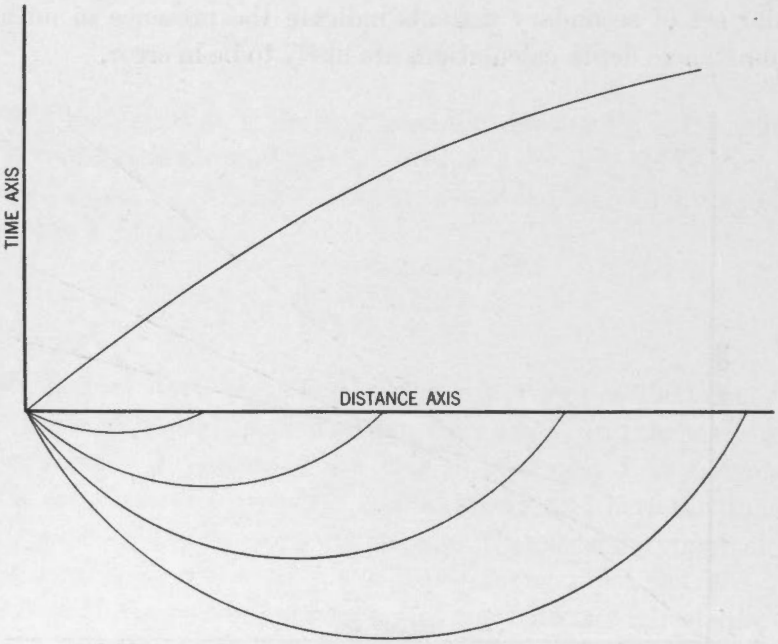


Figure 3—Ray paths and travel-time curves for a medium in which the velocity increases functionally with depth.

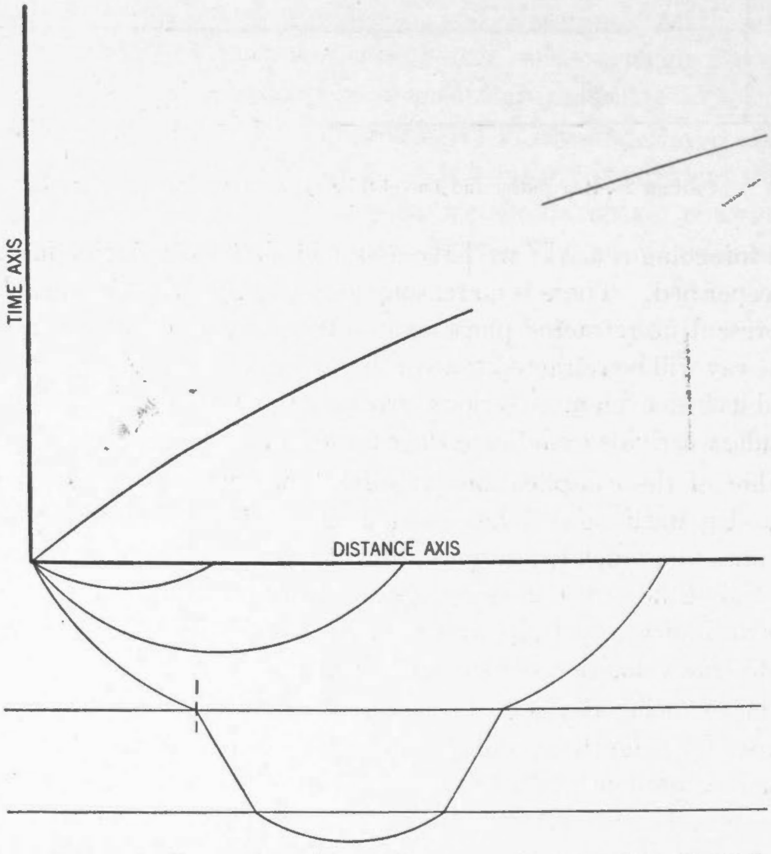


Figure 4.—Ray paths and travel-time curve where a medium in which the velocity increases as a function of depth is interrupted by a layer of lower velocity.

If ray paths are curved it is sometimes possible to detect the existence of a low-speed bed at depth. The situation is illustrated in Fig. 4. The ray which just grazes the low-speed bed determines the limiting distance at which the first segment of the travel-time curve can be observed. Rays penetrating at a steeper angle will be refracted into the low-speed bed, and so lost. We thus have a shadow effect and, because of time lost in the low-speed bed, a displacement of the travel-time curve. The same shadow effect, but without the displacement of the travel-time curve, can occur due to a discontinuity where the velocity increases directly. Rays steeper than the grazing one are either reflected at the interface or refracted along it at the higher velocity.

As one would expect, the travel-time equation for the curved ray paths is expressed as an integral equation. We shall postpone discussion of the equation until it is required. The main point of these introductory remarks is to make it clear that refraction seismology works through the analysis of travel-time curves. The field work to be described later in the paper was carried out simply to define the curve.

The above considerations have been based entirely on the methods of geometrical optics, without any regard to the energy which the refracted phases can carry. The mathematical study of the reflection and refraction of sinusoidal plane waves was carried out by Knott in terms of energy and by Zoeppritz in terms of amplitude. In each case one is led to a set of four linear equations with coefficients involving the densities and velocities of the two media. These equations may be solved for the ratio of the energy (or amplitude) of each of the four generated waves to the equivalent quantity for the incident wave. When one considers the critically refracted ray, to which we were led by the theory of geometrical optics, the simple theory indicates that it carries no energy. This must be regarded as an inadequacy of the theory. There is an overwhelming body of observational evidence, particularly from the field of seismic prospecting, to show that the methods of geometrical optics may properly be applied to the problem.

POSITION OF THIS WORK IN RELATION TO EARLIER CRUSTAL STUDIES

The history of seismic investigations of the crust dates from the pioneer work of A. Mohorovičić. In studying the records of an earthquake in Croatia, October 8, 1909, he obtained a travel-time curve consisting of two segments, and interpreted it as indicating the presence of a crust. Once the existence of the crust had been established it became desirable to determine its properties in as many areas as possible. The problem was of interest not only for its own sake but because a knowledge of crustal properties is necessary to many studies of the deep interior of the earth.

The early investigations centered largely in Europe and were based for the most part on the study of near earthquakes. As more and more detailed studies were attempted, additional layers were proposed to account for observed phases. The details varied, of course, from place to place, but in general two distinct layers were recognized. The upper of these two layers, with a thickness of the order of fifteen kilometres, was usually referred to as the 'granitic' layer, since geological evidence is strong that basement rock in the continents is usually granitic. With one or two exceptions the generally accepted P-wave velocity in this layer was of the order of 5·7 km/sec. Beneath this surface layer there was another layer, usually called the 'intermediate' layer, in which P-wave velocities were of the order of 6·5 km/sec. Most investigators found evidence of additional subdivision within this intermediate layer; in particular an upper and lower intermediate layer were usually recognized. The total thickness of the intermediate layers was about twenty km. Below the intermediate layer, or layers, one enters the region in which normal earthquake wave propagation occurs, and here the velocity found was usually of the order of 7·8 km/sec. All investigators agreed that there was a sharp discontinuity marking the base of the crust, and this was called the Mohorovičić discontinuity after its original discoverer.

In the latter stages of this initial period detailed work was also carried out in California, in southern California by the Pasadena group under Gutenberg, and in northern California by Byerly. These studies were most comprehensive, for not only were large numbers of local earthquakes available for study, but the seismic network in California supplied adequate numbers of suitably equipped stations operated with very good time control. The results in California did not differ, except in detail, with those found in Europe. Velocities of the same order were observed.

Studies were conducted in other parts of the world with earthquakes as energy sources and, while confirmation of what we may call the 'classical' crust was obtained, the results must be suspect. Due to the scarcity of recording stations investigators usually had to refer to tables based on the European or California results in order to select their phases. The studies naturally resulted in values similar to those on which the tables were based. Nevertheless there was a tendency to regard these results as additional confirmation of the standard interpretation.

In 1935 a Harvard University group working under the direction of Leet, began a study of the crust in New England. This investigation, in which he had the co-operation of the member stations of the North Eastern Seismological Association, utilized quarry blasting as a primary source of energy. The technique was to time blasts accurately at the source and to record them at the permanent stations of the member observatories. It was concluded that the structure in New England was similar to that found elsewhere, but the velocities in the several layers were markedly higher than those generally accepted. In particular the velocity of P-waves in the granitic layer was found to be in excess of 6 km/sec. instead of the usual value of 5·7.

This difference in velocity was so far beyond the probable errors indicated by the earlier work that many seismologists refused to accept Leet's values. Jeffreys, who had made many detailed studies of European earthquakes demanded greater proof of statistical validity than Leet was prepared to give. Gutenberg pointed out that ancient sediments often exhibit velocities higher than those in granite, and dismissed Leet's 'granitic' velocities as being due to propagation through superficial sedimentary layers. Such propagation could not occur in earthquake investigations since the source of energy was well within the crust.

Let us examine the relative merits of studies based on earthquakes and those using blasts. The fact that earthquakes occur at some depth within the earth is of no intrinsic disadvantage, since the formulae developed in our earlier section may readily be adapted to take account of focal depth. Unfortunately, however, the location, depth of focus and time of occurrence of the earthquake are all unknown, and must be determined from the same records which are subsequently analysed for crustal structure. This is not a happy situation and certainly would not be tolerated in more precise branches of physics. A further complication is provided by the fact that, in associating random earthquakes with a random distribution of seismograph stations, we are not likely to obtain a seismic profile lying along a single azimuth. This may possibly be interpreted as an advantage since it will result in an average value, but it will almost certainly lead to complication in interpretation.

Blasts, on the other hand, since they may be precisely located and timed, approach a desirable standard accuracy. Their principal disadvantage lies in their lack of focal depth, with the resulting possibility of propagation through surface layers. A further disadvantage is that explosives theoretically do not generate sufficient shear energy to allow an adequate study of shear waves. In actual practice it is found that, under favourable conditions, shear waves with reasonably large amplitudes are recorded.

It should now be clear why, when the first rockburst recorded in Ottawa, it occasioned so much interest. The distribution of energy between the longitudinal and shear waves showed that the bursts were similar to earthquakes in the mechanics of energy release. Virtually the rockbursts could be regarded as a series of earthquakes constrained to occur in an extremely localized area. Their precise location could be obtained by inspection in the mines and, by placing a seismograph at Kirkland Lake, their time of occurrence could be measured accurately. They appeared to possess the best advantages of both earthquakes and blasts. A preliminary study of the records from three stations was carried out by the present author[2]. Since the three stations were all beyond the last discontinuity in the travel-time curve, the conclusions could not be accepted as final. The study did, however, have the merit that the epicentres and epicentral times were known and that methods of analysis were used which were, for the most part, independent of previous results. The investigation, for what it was worth, sustained Leet's velocity values. But more important, it confirmed the merits of rockbursts as an energy source and gave an indication of the usefulness of a larger program such as the one to be described in these papers.

This later work, with stations situated within the boundaries of the Canadian Shield, had the further advantage that the instruments could in most cases be placed on Precambrian rocks. Only two of the stations were on Palaezoic rocks, and these outcrops were known to be very thin. Thus not only could propagation through surface layers be eliminated, but there were no complications of surface corrections such as existed in most other parts of the world.

In order to complete this historical review it should be mentioned that there have been several investigations going forward, more or less contemporaneously with the one here reported. Discussion of their results is reserved for a later section, but a brief listing will be given here. P. L. Willmore has led a British group in studying records from the Helgoland blasts and has co-operated with Hales and Gane in studying travel-times from rockbursts in South Africa. L. B. Slichter has made detailed studies in the northern United States, based on quarry blasts, and a group from the Carnegie Institution of Washington, under the direction of Dr. M. A. Tuve, has made blast-based studies in California and in the vicinity of Washington, D.C. In a general way all these studies have cast doubt on the existence of a multi-layered crust and have sustained the high velocity values found by Leet.

DESCRIPTION OF THE FIELD WORK

SOURCE OF SEISMIC ENERGY

The principal source of energy employed in this investigation has been the rockbursts which, from time to time, occur in the Kirkland Lake camp. Rockbursts are due to the impulsive failure of rock under stresses induced by mining operations. As the rock is removed very severe stresses are built up in the remaining pillars even if back-filling is employed. In most mining areas the rock fails as the forces are applied and no dangerous pressures can build up. But in some other areas, owing to the competence of the rock and possibly to the structural characteristics of the mine, the remaining rock withstands the forces and stores up elastic energy until violent rupture occurs. The release of energy may occur as a slipping or it may occur as an impulsive dilatation; it may occur in the actual workings or at some distance from them within the walls.

Rockbursts became a serious problem in the Kirkland Lake camp about 1936. As has already been mentioned, these early bursts provided data for a preliminary study and suggested that further work should be done in the field. This additional program had to be postponed because of the war. During the intervening period a very large amount of study had been devoted to the rockburst problem and the mines had succeeded in reducing the number and intensity of the bursts by careful back-filling, by appropriate mining methods and by so controlling their occurrence that there is a minimum of danger to the miners. It should be a matter of great satisfaction to the mine management that none of the rockbursts which have contributed to the latter sections of this research has resulted in fatalities.

The mines of the Kirkland Lake camp occur along a break, or system of faults, trending approximately N 63° E, the principal mines of the area occupying a distance of about 3 miles along the break. Mining has proceeded to a depth of approximately 6,300 feet below sea level. Because of the dimensions of the workings it was not possible to have the new seismograph station, installed to record the time of occurrence, precisely at the source of the bursts. The station was installed at a location selected for its convenience on other grounds. A correction has had to be applied to observed times to determine the actual time of occurrence of the bursts.

DATA TO BE DISCUSSED

Throughout this paper we shall have to refer to two sets of data. The first set is that provided by rockbursts recorded at the regular earthquake stations of Eastern Canada and New England. These data derive largely from the initial program and, while they were obtained without the necessity of any field work, the recording speed and time-correction technique could not be controlled. We shall refer to stations contributing to the section of the work as 'distant' stations, since they all lie at distances greater than 450 km.

The second set of data derive from the field work carried out during the years 1947–1951. We shall refer to the stations involved in this work as the 'field' stations, or as the 'near' stations. It should be borne in mind that the description of field technique which follows applies only to these near stations.

INSTRUMENTAL REQUIREMENTS

The introduction stressed the advantage enjoyed by rockbursts as a source of energy for crustal studies, and suggested that the same order of accuracy could be attained with bursts as with blasts. This order of accuracy is not easily arrived at. Where blasts are utilized it is possible to know the time of occurrence in advance and the recording stations need only be occupied briefly at the appropriate times. High paper speeds can be used and electronic amplification can be utilized without fear of variation in characteristics throughout the period of recording.

The rockbursts presented a somewhat different problem. Their approximate location was known in advance but there was no indication of when they would occur. It was thus necessary to record continuously. It was also necessary that the recording stations be unattended except when the sheets were changed; for this reason electronic amplification was considered to be undesirable. Timing had to depend upon the continual maintenance of absolute time.

It was recognized that continuous operation at the high paper speed required for precise work could only be maintained if a field party were in direct charge of the operation. Because of the climate and the limited availability of student assistance, this could only be accomplished during the summer. Rather than waste the winter months, it was decided to occupy stations remote from the source as conventional seismic stations and to occupy the nearer ones at the advanced paper speed during the summers. Amongst the 'field' stations we shall then distinguish between the 'summer' and the 'winter' stations, the former being operated with special techniques to be described, the latter operated as conventional seismograph stations, serviced by local residents. The summer program progressed so well that it was eventually possible to carry the summer stations to a point beyond the first of the winter locations.

By the time the program was begun, the mines had succeeded in exercising a large measure of control over the rockbursts, with the result that they occurred infrequently and were of much less intensity than before the war. The principal problem of instrumentation has been to obtain seismometers of appropriate sensitivity without the use of electronic amplification.

DETAILS OF THE FIELD PROGRAM

Recording Equipment

Various combinations of seismometers and galvanometers were employed during the life of the project but in all cases recording was by galvanometer on photographic paper. Sprengnether microseismic recorders were used, a single-component drum being operated at Kirkland Lake and three-component drums at the two field stations. These recorders, designed for use in the study of microseisms, have paper speeds selective at 60, 112, 150 and 281 mm. per minute. The drum speed is controlled by synchronous motors. Time marks are placed on the records at one-minute intervals by a chronometer, and this chronometer can be rated by the recording of radio time signals.

Seismometers

Sprengnether Series D–H short-period seismometers were used initially throughout the project, a vertical being operated at Kirkland Lake, and a vertical and two horizontals at each of the two field stations. The period of these instruments was 1·8 seconds, their synchronous magnification approximately 5000. It soon became apparent that shorter period and higher magnification would be required. A prospecting-type geophone with a period of about 0·02 seconds was installed at Kirkland Lake and proved extremely satisfactory for recording the bursts. At the field stations the first step taken was to reduce the period of the Sprengnether seismometers to 1·0 seconds and to operate them with Micro-Moll galvanometers having a period of 0·33 seconds. This combination was satisfactory as far as period range was concerned and yielded very good records in the case of large bursts, but it had too low magnification to allow the great majority of bursts to be recorded. Amplifiers were constructed for the combination and, while they presented some difficulties in maintenance, provided a satisfactory stop-gap. In 1949, with the help of Dr. E. C. Bullard, it was possible to make tests of a new type of seismometer recently designed by Willmore[3] at Cambridge, England. This proved so extremely sensitive that, with the permission of Willmore and Bullard, six additional seismometers were constructed by the Sharpe Instrument Company, Toronto. In the final year of the program, these instruments were used exclusively at the field stations.

Table I shows the various combinations used in the field stations as well as in the permanent observatories which have contributed records to the project.

TABLE I

Instrumental Combinations Used in the Project

Designation	Seismometer type	Seismometer period, seconds	Galvanometer type	Galvanometer period, seconds	Magnification if known
A	Heiland	0·02	Heiland	0·02	(200)
B	Sprengnether	1·80	Leeds and Northrup	1·80	5000
C	Sprengnether	1·00	Micro-Moll	0·33	(2000)
D	Sprengnether with Wagg Amplifier	1·00	Micro-Moll	0·33	(2500)
E	Sprengnether	1·00	Downing[4]	0·03	?
F	Willmore	0·3	Downing	0·03	10^5
G	Benioff	1·0	Benioff	0·2	7000–15000
H	Wood-Anderson	1·0	—	—	2200

The Willmore seismometers have, because of their extreme sensitivity, made possible the completion of the project within a reasonable time. In their original form, as used by us, they do not represent the ideal solution to the instrumental problem of recording near earthquakes. The combination has too short a period and admits phases with a wave length of the order of one-half km. Such a spectrum will undoubtedly include phases propagated through local structures, for the local structures in the Shield have, in general,

---

[3] Willmore, P. L.—"The Theory and Design of Two Types of Portable Seismograph", *M.N.R.A.S. Geoph. Suppl.*, Vol. 6, No. 2, 129–137, 1950.

[4] Downing, A. C.—"The Construction of Micro-Galvanometer Systems", *Journal of Scientific Instruments*, Vol. 25, No. 7, 230–231, 1948.

dimensions great with respect to this wave length. The extreme complexity of the records obtained by the Willmore seismometer, which makes the interpretation of secondary phases extremely difficult, is almost certainly due to this factor. Fortunately, records of major bursts were obtained by the modified Sprengnether seismometers at distances of approximately 50, 100 and 175 km., and these much simpler records have been invaluable in the interpretations.

It should be mentioned in connection with the above remarks that Willmore has since produced a seismometer with period characteristics very similar to the Benioff, and that this instrument is now available commercially. The new instrument should be an ideal one for the study of near earthquakes and similar problems.

Power Supply

All but one of the summer stations were at points where no hydro-electric power was available. This situation was met by the use of vibrators powered by storage batteries, to supply the alternating current necessary to operate the recorders and the radios. The details of this arrangement, as well as the design of the amplifiers mentioned in the preceding section, were worked out by D. M. Wagg[5]. The storage batteries were changed daily and charged at the base camp. This method of power supply is recommended to anyone who must operate synchronous motors at remote locations. While the frequency varied throughout the life of the batteries, it did so gradually and the length of successive minutes showed satisfactory constancy.

The Kirkland Lake Station

In order to time the blasts near their source, a new seismograph station was constructed at Kirkland Lake, the earlier one having been dismantled. This station, of concrete construction, is heavily insulated and is heated by thermostatically controlled electric heaters. No piers were provided; the galvanometers and recorder are placed on heavy steel tables and the seismometer rests upon the concrete floor of the vault. A local resident acts as operator of this station.

The Field Stations

In designing the huts to house the field stations it was desired that portability be combined with sufficient ruggedness to withstand frequent moving, and that they be heavily enough insulated to meet the severe northern winters. The problem was very satisfactorily solved by Mr. W. C. O'Neil, the Observatory carpenter. The huts are eight feet square and six feet high, with a vestibule to serve as a light trap. They are constructed of masonite on a framework of two-inch scantling, the wall space being completely filled with insulating material. They can be disassembled in seven easily transportable sections. During the winter months they are heated by thermostatically controlled electric heaters. The success of these huts may be said to have pointed the way for the installation of the seismograph at Resolute Bay[6], although much heavier buildings are used in the Arctic location.

---

[5] Wagg, D.M.—"Electric and Electronic Equipment Used on Kirkland Lake Seismic Survey", B.A.Sc. Thesis, Jniversity of Toronto, 1949.

[6] Bremner, P. C.—"The Dominion Observatory Seismic Station at Resolute Bay, Northwest Territories", *'ublications of the Dominion Observatory*, Vol. XVI, No. 2, 1952.

In preparing a site for occupancy, it was necessary to construct a low foundation for the hut and small piers for the recorder and galvanometers. Usually a small auxiliary building was poured of concrete to house the seismometers. A portable insulated roof was used on this building. The preparation of the site was normally carried out well before it was required and could be completed in about three days.

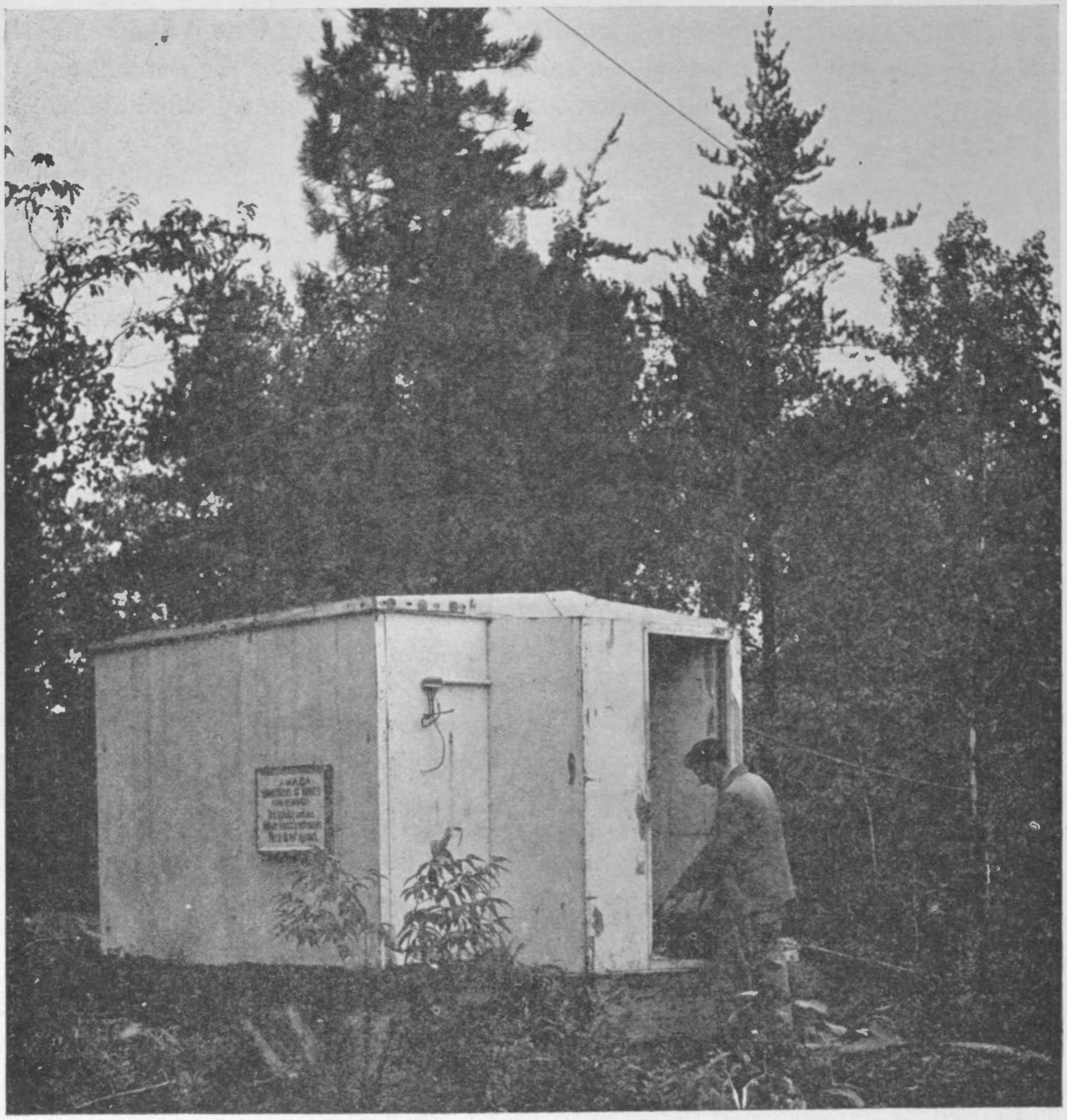


FIGURE 5—The portable hut as installed at the Shoomogan station. The vestibule, which serves as a light trap is removable in a single section. The roof is made up of two sections with a metal strip covering the join. Each wall is transported separately. Note the input for electric power which could be used where mains power was available. (Photo by George Hunter.)

Once the site had been prepared it was possible to take a station out of operation after breakfast, move it as much as thirty miles, and have it in routine operation by supper time. A two-ton truck was permanently assigned to the party for moving the stations. In addition a car or a small truck was usually available for the lighter jobs.

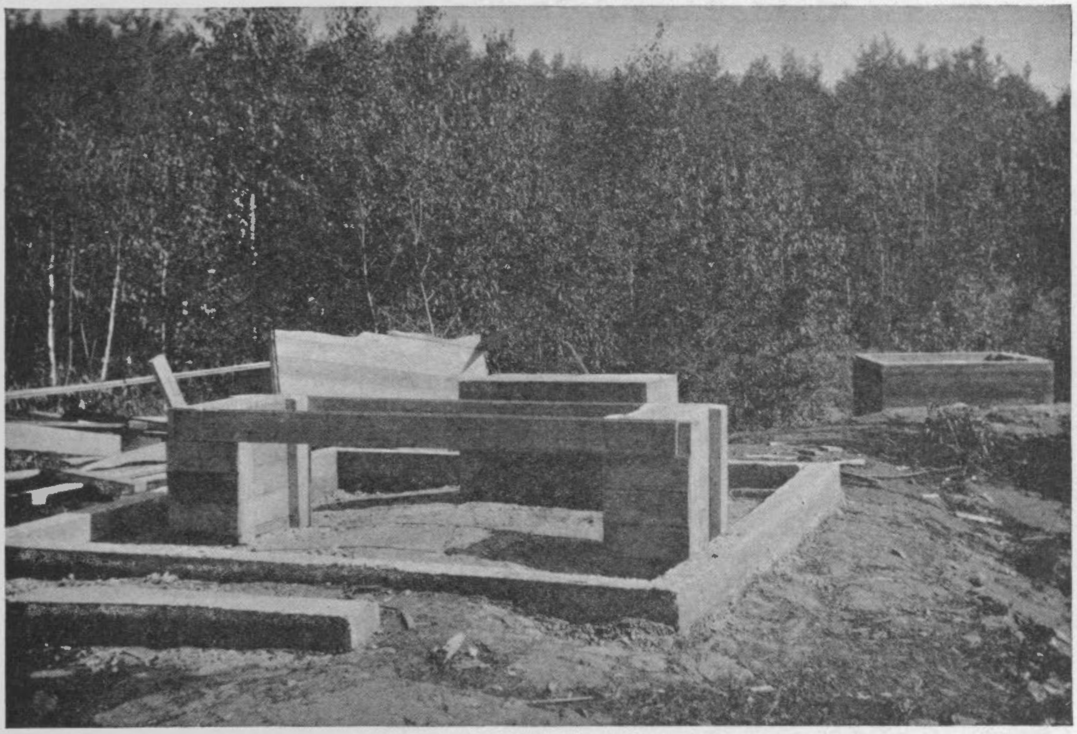


FIGURE 6—The site of the Tarzwell station before the installation. In the background is the shelter for the seismometers. In the foreground are the foundations for the hut and vestibule, a large pier for the galvanometers and the two small piers on which the recorder rested.

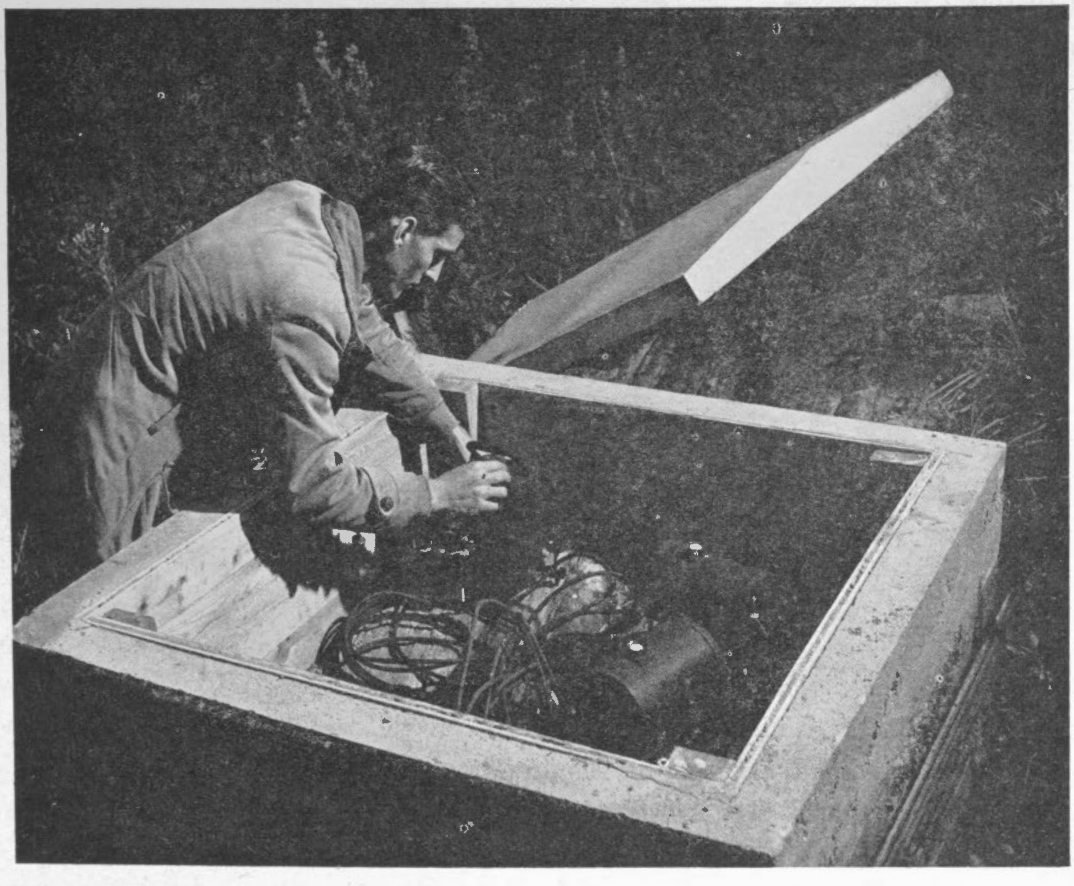


FIGURE 7—The Willmore-Sharpe seismometers installed at the Shoomogan station. Note the insulated roof for the seismometer building. (Photo by George Hunter.)

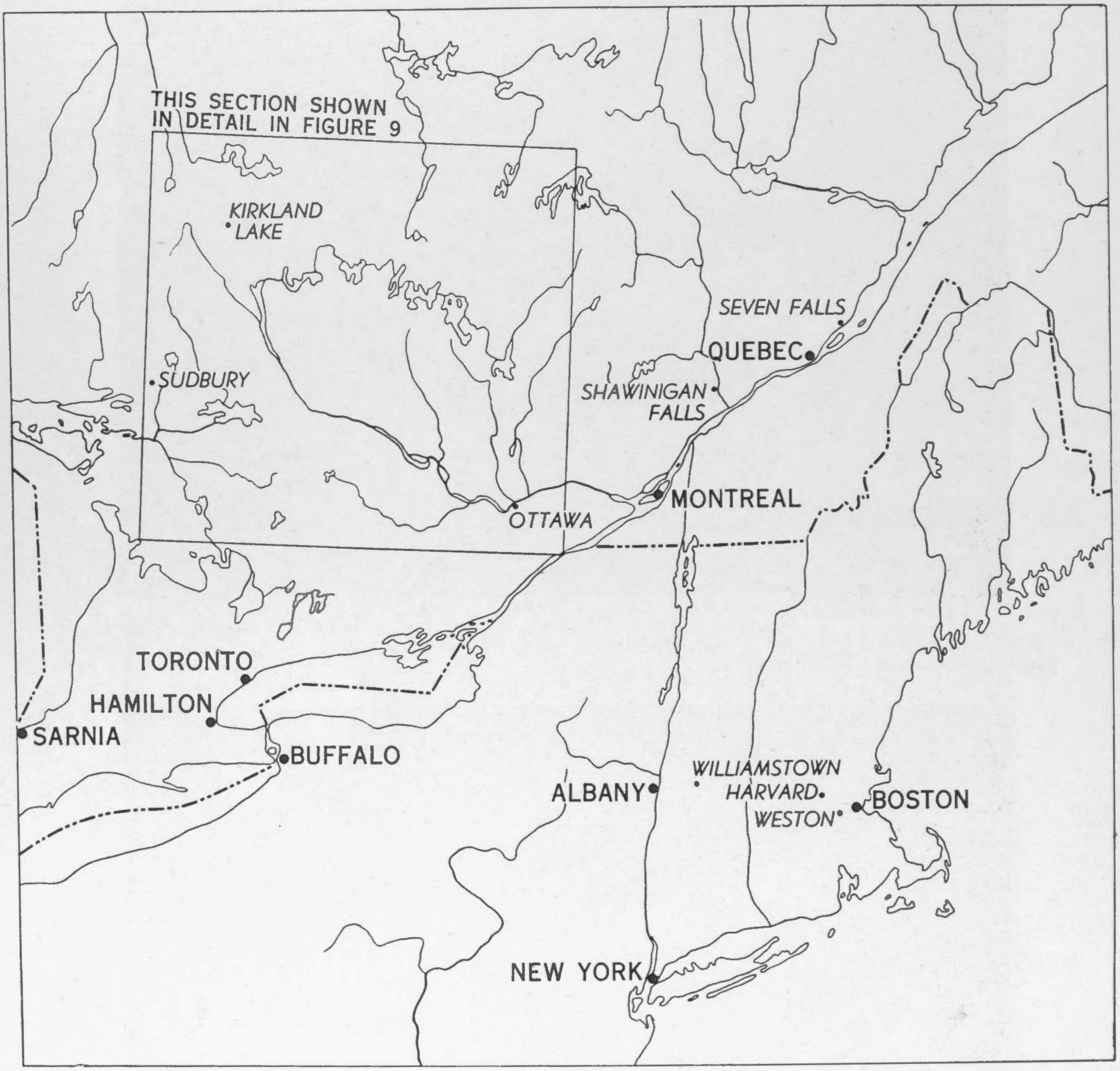


FIGURE 8—Sketch map showing the location of the survey. Places mentioned in the text are shown in slanting letters.

Stations Occupied

The project was begun in July, 1947, and continued until May, 1951. The stations occupied during this period are shown in the maps of Figs. 8 and 9. More precise data are provided by Table II, which gives the geographical co-ordinates of each station, their approximate distance and azimuth from Kirkland Lake, their elevations, and an indication of the type of rock upon which they were located. Ville Marie I, Temiskaming, La Cave

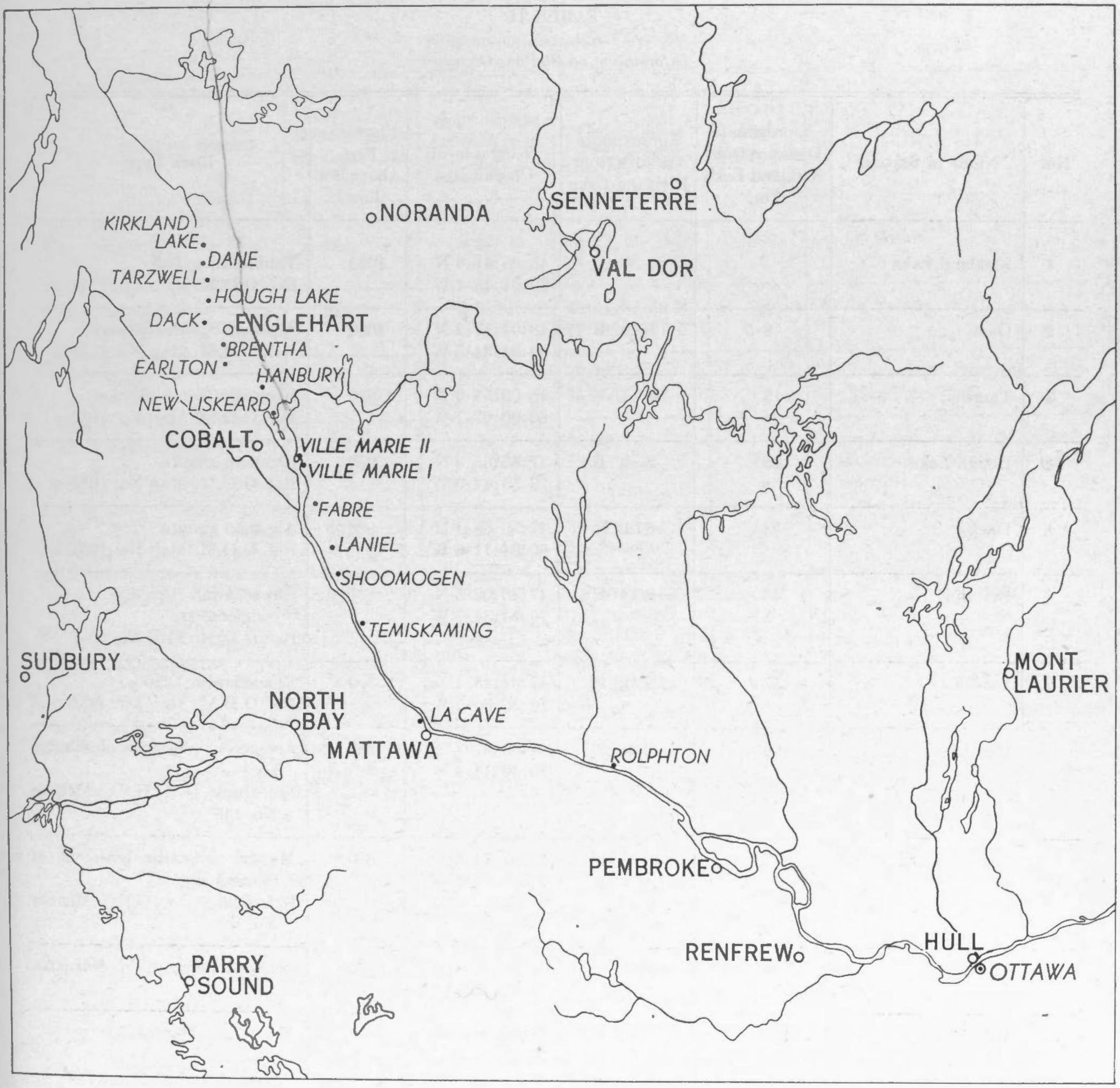


FIGURE 9—Sketch map showing the location of the field stations. Place names with slanting letters are locations of seismograph stations.

and Rolphton were occupied as winter stations with paper speeds of 60 mm. per minute. Rockbursts were never satisfactorily recorded at either La Cave or Rolphton, but the stations are included in Table II as a matter of convenience since they provided data to be analysed in the second paper of this series. As explained earlier, the stations at Ottawa, Shawinigan Falls, Williamstown, Harvard and Weston are the regular seismograph stations at those points which have yielded information in the course of their normal operation.

TABLE II

Information on Stations Occupied

No.	Name of Station	Approximate Distance from Kirkland Lake km.	Approximate Azimuth from Kirkland Lake	Geographical Coordinates	Elevation Feet Above Sea Level	Rock Type
1	Kirkland Lake			48:08:41·4 N 80:01:45·1 W	1020	Timiskaming Tuff Ref. O.D.M. Map No. 1945–1
2	Dane	8·5	S 10° E	48:04:17·2 N 80:01:34·5 W	1060	Algoman Syenite porphry Ref. O.D.M. Map No. 1934–a
3	Tarzwell	15	S 14° E	48:00:54·0 N 80:00:07·7 W	1030	Keewatin Iron formation Ref. O.D.M. Map No. 1934–a
4	Hough Lake	25	S 9° E	47:55:35·3 N 79:59:44·9 W	950	Algoman granite Ref. O.D.M. Map No. 1934–a
5	Dack	33	S 4° E	47:50:38·1 N 80:01:11·5 W	960	Algoman granite Ref. O.D.M. Map No. 1934–a
6	Brentha	44	S 14° E	47:46:02·5 N 79:54:34·7 W	860	Keweenawan (Cobalt) conglomerate Ref. O.D.M. Map No. 50–j
7	Earlton	52	S 12° E	47:41:45·4 N 79:53:30·7 W	890	Keweenawan Diabase Ref. O.D.M. Map No. 1934–a
8	Hanbury	66	S 25° E	47:36:37·7 N 79:40:14·4 W	860	Arenaceous limestone of Silurian age Ref. Hume, G. S., G.S.C. Memoir No. 145
9	New Liskeard	77	S 25° E	47:31:14·4 N 79:36:34·5 W	800	Massive dolomitic limestone of Silurian age Ref. Hume, G. S., G.S.C. Memoir No. 145
10	Ville Marie II	99	S 26° E	47:20:53·31 N 79:27:17·34 W	800	Lorrain quartzite of Huronian age
11	Ville Marie I	102	S 26° E	47:19:20·99 N 79:26:57·72 W	627	As for Ville Marie II
12	Fabre	120	S 25° E	47:10:32·65 N 79:21:31:78 W	760	Pre-Huronian Batholithic rocks not further differentiated on available maps G.S.C. 145A, 155A, 820A
13	Laniel	139	S 25° E	47:00:46·6 N 79:16:42·8 W	1020	As for Fabre
14	Shoomogan	152	S 23° E	46:53:19·5 N 79:14:26·2 W	910	As for Fabre
15	Temiskaming	174	S 24° E	46:43:02·10 N 79:06:07·72 W	690	As for Fabre

TABLE II—*Concluded*

Information on Stations Occupied

No.	Name of Station	Approximate Distance from Kirkland Lake km.	Approximate Azimuth from Kirkland Lake	Geographical Coordinates	Elevation Feet Above Sea Level	Rock Type
16	La Cave	221	S 27° E	46:22:43·70 N 78:43:48·53 W	580	As for Fabre
17	Rolphton	282	S 39° E	46:11:06·59 N 77:41:40·27 W	480	As for Fabre
18	Ottawa	451	S 47° E	48:23:38 N 75:42:57 W	272	Boulder clay overlying Ordovician limestone
19	Shawinigan Falls	578	S 72° E	46:33·1 N 72:45·8 W	197	Precambrian rocks, not differentiated on available geological map 704A
20	Williamstown	807	S 41° E	42:42:51 N 73:12:40 W	718	
21	Harvard	920	S 47° E	42:30:26 N 71:33:45 W	591	
22	Weston	943	S 47° E	42:23:00 N 71:19:20 W	213	Gabbrodiorite

PRECISION OF THE DATA TO BE ANALYSED

INTRODUCTORY REMARKS

It will be apparent from the introduction that the theory on which the study is based is extremely simple. The value of the work will depend upon the precision with which time and distances are measured. In all cases distances between bursts and recording stations have been computed from the geographic co-ordinates of the two points. The precision with which distance is known is thus a function of the accuracy with which the positions have been determined. The time required for energy to travel from a burst to the recording station is observed as the difference between the time of occurrence of the burst and the time of arrival of the energy at the station. In this section the accuracy with which these measurements of time and position could be made will be discussed.

ACCURACY OF DISTANCE MEASUREMENTS

Location of Positions

Stations 1 to 9 of Table II were located on maps with a scale of 4″ to the mile. These maps, not yet published, were supplied in preliminary form by the Ontario Department of Lands and Forests. Each location was made by careful chaining to road corners or other significant features. The geographical co-ordinates were then read off the maps by proportional parts. The co-ordinates of these stations may be considered as accurate within about ±0·2 seconds of arc.

In the case of stations 10 to 15 inclusive, which lay in Quebec, no large scale maps were available. At our request the Geodetic Survey of Canada very kindly sent a special party into the field to obtain these co-ordinates. Stations 10, 11, 12 and 15 were located by traverse from primary triangulation points. Stations 13 and 14 were located by astronomic observation, correction being made for the deflection of the vertical.

The stations at La Cave and Rolphton were located on large-scale surveys of the Hydro Electric Power Commission of Ontario, which surveys are tied to geodetic monuments. The computation of the geographical co-ordinates was carried out by officers of the Geodetic Survey. The information about the permanent stations (18–22) was obtained from the station bulletins.

Elevations are not critical to the same extent as distances. The elevations of all the temporary stations (1–17) were determined by use of an aneroid altimeter, the usual precautions in the use of this instrument being carefully observed.

The geographic co-ordinates of the bursts were obtained in the following way. Each mine supplied the location of the bursts on its property with reference to its shaft. The position of the burst could then be plotted on the large scale map sheet and its co-ordinates read off by proportional parts. At the same time the distance to the Kirkland Lake station was scaled off, the difference in elevation between burst and station noted, and the hypotenuse of the triangle computed to give actual separation of burst and station. This distance was used in a time correction to be discussed later.

Calculation of Distances

Distances were computed using the method recommended by Richter[7] for the calculation of short distances. Richter's tables apply only for latitudes from 30° to 40°. It was necessary to extend them to latitude 50° for this work.

Accuracy of Distances

Richter has shown that for distances of less than 500 km. the method of computation used is accurate within 0·01 km. The location of the stations is accurate within about ± 0·01 km. In the case of the smaller bursts which did not shatter large sections of the workings, the locations of the bursts had about the same accuracy. In the case of larger bursts it was necessary to assume that the energy was released from the centre of the disturbed volume, an assumption which was not perhaps always justified. In the main, however, it seems reasonable to suppose that the possible error of distance in the case of a precisely located burst was of the order of ± 0·03 km. with the actual error being probably much less.

ACCURACY OF TIME READINGS

General Remarks

We shall now examine the accuracy with which travel times are measurable on the records, having regard to the necessity of chronometer corrections. Different paper speeds were used during different periods of the work. The paper speed was dictated by geographical considerations. During the first three summers when only one field station

---

[7] Richter, C. F.—"Calculations of Small Distances", *Bull. Seism. Soc. Am.*, Vol. 33, 243–250, 1943.

was being operated, and that in an area of good roads, it was possible to change the records three times each day and a paper speed of 150 mm/min. was used. During the final summer, two field stations were being operated in an area of bad roads and it was necessary to reduce the paper speed to the 112 mm. setting and the consequent two daily changes. In the case of either of these paper speeds, it is possible to read the position of any event to four significant figures. This would, in general, suggest an accuracy of 0·01 seconds. Readings will be given to this figure but equivalent accuracy is not claimed. Variations in drum speed, differential shrinking of the paper in the developing process, and reading errors introduce variations of some few hundredths of a second. Further reference will be made to this matter after discussing the time corrections.

Method of Making Time Corrections

As mentioned above, time marks were placed on the records at one minute intervals by chronometers. These chronometers were rated, radio reception permitting, by two sets of time corrections at each record change. The mechanism for recording the chronometer minutes will first be examined.

In the Sprengnether recorder time marks are placed on the sheet by the deflection of the light beam. This deflection is accomplished by the closing of a relay which carries a prism through which the beam passes. It was the intention of the manufacturer that these relays should be operated directly by the chronometer contacts. However, it has been our experience that they draw so much current as to damage the chronometer contacts, and a second relay was placed between the prism-bearing relays and the chronometer. This second relay was operated either by the chronometer contacts or by the radio time-signals as desired. Since the radio signals are operating precisely the same circuit as is the chronometer, any delay in the operation of the two relays is the same for each and therefore does not lead to any error.

The radios employed for the reception of time signals had a power-amplifying and rectifying stage added at the output to operate a third relay which we shall refer to as the radio relay. Any delay in the closing of this radio relay would lead to an error in chronometer rating since there is no equivalent delay in the closing of the chronometer contact. By employing high-resistance relays of good design this delay was reduced as much as possible and by employing identical relays in both the Kirkland Lake and field radios the effective error, which is the difference in the delay of the two relays, should be small. The delay of one typical relay was measured and was found to be slightly less than 0·02 sec. If this figure may be accepted as approximately correct for all the relays, then the *difference* in the delay between two stations is of a negligible amount.

In making time corrections, signals were recorded continuously throughout a minimum period of four minutes, the signal being cut off to permit the undisturbed recording of the chronometer minute marks. A section of a typical example is shown, full scale, in Fig. 10.

FIGURE 10—A section of a typical time-correction, reproduced full scale. The larger displacements are chronometer minute marks, the smaller ones radio seconds. A switching arrangement, manually operated, prevented superposition of the two sets of signals.

In each of the four minutes the distance to each of about ten of the second marks was read on a fine scale, as well as the length of the minute. Proportional parts then give the reading of the several seconds, which should vary in the seconds but agree in the decimal since they are at precisely second intervals. This was repeated for each of the four minutes and an average taken of the decimal in each case. This decimal was then applied to the proper second and the time correction computed. When corrections had been obtained for the signals immediately preceding and immediately following the event to be timed, a straight line graph was drawn joining them and the correction read off the graph.

Accuracy of Time Corrections

The method by which time corrections were obtained permits a determination of the accuracy of the result. In a typical correction corresponding to the signal shown in Figure 10, the lengths of the four minutes varied between 108·3 and 108·7 mm. In making the time correction 42 observations were taken, spread throughout the four minutes. The mean of the decimals was taken and the variations from this mean used to determine the probable error of the mean. This proved to be 0·007 sec. This process was repeated for 12 other time corrections chosen completely at random throughout the notes of three years. The probable error of the means in these cases were 0·007, 0·006, 0·007, 0·005, 0·007, 0·005, 0·006, 0·006, 0·005, 0·003, 0·005, 0·006, the average probable error for the 13 tests being slightly less than 0·006 sec. It is clear then that the probable error of a single time correction is, to the order of accuracy employed, 0·01 sec.

To obtain the time correction corresponding to any event, it was necessary to depend on graphical interpolation between the two bracketing time corrections. If each of these has a probable error of 0·01 sec., the probable error of an interpolated correction will be not more than 0·01 sec., supposing the chronometer rate to be linear. To ensure that this rate remained constant, the chronometers were wound at every change and so were operated in the same range of spring tension at all times. We conclude that the probable error of a time correction is of the order of 0·01 sec.

Accuracy in Reading a Single Event

Later in this paper we shall obtain an estimate of the probable errors of elapsed times observed at the several recording stations. The residuals from which this error derives will be due not only to observational errors but also to variations in rock type along the traverse. In order to appraise the effects of the latter conditions, it is desired to make an estimate of the probable errors introduced by the mechanics of obtaining the readings. An event, by its very nature, never repeats itself exactly, and there is no direct means of obtaining the desired quantity. The error sought arises from several causes—error in reading, variation in drum speed and differential shrinking of the paper in developing. These same factors obtain in making the time corrections. The desired probable error should therefore be approximated to by studying the variations from their respective means of an appropriate number of time observations selected at random from an equal number of different minutes. In making this test thirty observations were used and they showed that the probable error of a single observation was of the order of 0·04 sec.

Accuracy of End Correction

One final source of timing error remains to be discussed. Since the Kirkland Lake station was not at the actual point of the burst, its record did not give the true time of occurrence but only the time at which the first wave reached the station. It was necessary to apply a correction to allow for this. The true distance between the burst and the station was determined in each case by the methods outlined earlier. This distance was divided by an appropriate velocity to give a correction, which was subtracted from the observed station time to give the true time of occurrence. It will be shown later that the velocity used in determining the correction was accurate within the limits of the problem. In the case of located bursts the error of the end correction was not significant.

The Probable Error in a Time Observation

In obtaining the elapsed time of any event it is necessary to subtract the corrected Kirkland Lake time from the corrected field station time. The probable errors of two readings and two corrections are then involved. The probable error of any elapsed time observation is then of the order

$$\begin{aligned} \text{P.E.} &= \sqrt{(\cdot 01)^2 + (\cdot 01)^2 + (\cdot 04)^2 + (\cdot 04)^2} \\ &= 0\cdot 06 \text{ sec.} \end{aligned}$$

SUMMARY

The various considerations outlined above have been summarized in Table III, which also introduces the notation to be employed in a subsequent table. The value of an observed event will there be indicated by three letters as, for example, aaa. The first letter will refer to the precision with which the burst is located, the second to the dependability of the time observations and the third to the quality of the records. The significance of the various letters is explained in Table III.

When the location of a burst is known only approximately, an error is introduced in the zero-correction and also in the distance assumed to the field station. The magnitude of these errors is estimated for the several categories of location and included in Table III. The error in distance due to uncertainty of location is surprisingly small. This is because the stations are nearly south of Kirkland Lake through which the fault runs in an east-west direction. An explanation of an "approximately located" burst is in order. These bursts occurred in the wall rather than in the actual workings, but displaced rock in adjacent stopes. The accuracy of their location does not differ significantly rom that indicated by "a". An inferred position, indicated "c", is much less accurate, s indicated in the table. Such bursts could be located in a certain section of the camp on the basis of the S–P interval in the Kirkland Lake records and on the reports of miners who heard them underground.

A time observation of category "a" is of the order found in the earlier analysis. Designation "b" has been used where time corrections are poor, or where no time corrections were recorded close to the event due to poor radio reception, and has automatically been applied to all 60 mm/min. records. Bursts designated "c" are so poorly timed that they have not been used in the reduction of observations except for interval considerations. All the errors indicated refer to first arrivals. The errors in reading later arrivals may be much higher.

The designations relative to the quality of the records are fully explained in the Table.

TABLE III

Designations of Quality of Observations

Letter	Designation	Explanation		
First letter refers to location of burst			Possible error in distance to recording station	Possible error in time of observation
	a	Precisely located	± 0·03 km.	
	b	Approximately located	± 0·03 km.	
	c	Inferred	± 0·10 km.	± 0·06 secs.
	d	Unknown	± 0·30 km.	± 0·15 secs.
Second letter refers to accuracy of combined time observation			Probable error exclusive of possible errors due to uncertainty of burst location	
	a	Good	± 0·06 secs.	
	b	Less satisfactory	± 0·1 to ± 0·2 secs.	
	c	Poor	± 0·2 to ± 0·5 secs.	
	d	Untimed event		
Third letter refers to record quality	a	Ideal amplitude, large enough to show all phases but not so large as to obscure secondary arrivals		
	b	Large emplitude, first phase sharp, later phases off scale		
	c	Small amplitude, only principal phases observed		
	d	Very small amplitude, observations in doubt		

MISCELLANEOUS CONSIDERATIONS

TABULATION OF BURSTS

Table IV lists the date and time of occurrence of those rockbursts which have contributed data for analysis. The station at which the record was obtained is indicated (reference Table II), the type of instument in use at the field station is given (reference Table I) and the paper speed at the field station is listed. An indication of the quality of the observation is given next (reference Table III). Finally the elevation of the burst is tabulated.

TABLE IV

Data on Bursts Contributing Records for Analysis

Event number	Date	Corrected Time of Occurrence E.S.T.	Recorded at Station No. (Reference Table II)	Components in Operation	Instrument Type (Reference Table I)	Paper Speed mm. per minute	Quality of Observation (Reference Table III)	Elevation of Bursts —feet above Sea Level
1	06-23-48	00:53:13·02	2	Z NS	D	150	abb	−3000
2	06-24-48	21:07:06·17	2	Z NS	D	150	aba	−2050
3	07-05-48	06:18:44·61	2	Z NS	D	150	aaa	−2600
4	07-15-48	18:28:42·18	3	NS EW	D	150	bba	−3500
5	07-15-48	18:32:37·07	3	NS EW	D	150	bba	−3500
6	07-24-48	21:29:49·21	3	NS	D	150	aba	−2050
7	07-28-48	05:24:40·59	4	NS EW	D	150	aba	−3130
8	07-28-48	06:39:32·59	4	NS EW	D	150	aba	−3130
9	07-30-48	13:29:59·67	4	NS EW	D	150	aba	−3300
10	09-06-48	14:54:01·59	5	NS	D	150	aab	−2730
11	07-26-49	12:25:39·07	6	NS	F	150	abb	−2700
12	07-27-49	17:32:46·61	6	NS	F	150	cba	−2000
13	07-27-49	20:09:50·85	6	NS	F	150	abb	−3300
14	07-29-49	20:04:00·14	6	NS	F	60	baa	−3300
15	08-11-49	13:32:10·06	6	EW	F	150	cbc	−2000
16	08-11-49	13:46:15·73	6	EW	F	150	cbc	−2000
17	08-19-49	16:43:00·86	6	EW	F	150	cab	−2000
18	08-30-49	14:18:57·16	7	Z NS	E	150	aaa	−3200
				NE	F	150	aab	
19	09-01-49	01:35:56·93	7	Z NS	E	150	aac	−1800
				NE	F	150	aaa	
20	05-19-50	13:35:00·21	8	Z R T	F	112	aad	−3900
21	06-14-50	19:39:35·21	8	Z R T	F	112	daa	−2000
22			9	Z R T	F	112	daa	
23	06-22-50	12:52:49·37	8	Z R T	F	150	aaa	−4500
24			9	Z R T	F	150	aaa	
25	06-23-50	00:24:20·27	8	Z R T	F	112	daa	−2000
26			9	Z R T	F	112	daa	
27	06-30-50	22:00:55·65	10	Z R T	F	112	aaa	−4300
28	07-01-50	22:34:16·65	10	Z R T	F	112	aab	−2050
29			12	Z R T	F	112	aaa	
30	07-08-50	14:24:24·32	12	Z R T	F	112	aac	+ 70
31	09-14-50	17:17:13·72	13	T	F	112	aac	−3500
32	09-14-50	17:17:17·76	13	T	F	112	aac	−3500
33	09-12-50	15:22:16·81	14	Z R T	F	112	aaa	−4000
34	11-27-48	17:20:10·02	15	Z	C	60	cba	−1000
				NS EW	B	60	cbd	
35			17	Z	B	30	cbd	
36			18	Z	G	60	cbc	
37			19	NS	H	60	cbd	
38	11-27-48	17:22:57·29	15	Z	C	60	cbc	−1000
				NS EW	B	60	cbd	
39			18	Z	G	60	cac	
40	12-01-48	09:21:47·79	11	Z	C	60	aba	−1000
41			15	Z	C	60	aba	
42	12-11-48	02:07:38·05	15	Z	C	60	abc	−3100
43	12-27-38	23:49:49·1	18	Z	G	60	aba	−1600
44	03-11-39	20:14:06·1	18	Z	G	60	abc	−2400
45	03-28-39	13:09:27·6	18	Z	G	60	abd	−1900
46	08-31-39	02:51:53·1	18	Z	G	60	aba	−2500
47	08-31-39	03:01:55·1	18	Z	G	60	aba	−2500

TABLE IV—*Concluded*

Data on Bursts Contributing Records for Analysis—Concluded

Event number	Date	Corrected Time of Occurrence E.S.T.	Recorded at Station No. (Reference Table II)	Components in Operation	Instrument Type (Reference Table I)	Paper Speed mm. per minute	Quality of Observation (Reference Table III)	Elevation of Bursts —feet above Sea Level
48	09–02–39	13:44:50·1	18	Z	G	60	aba	−2700
49	09–19–39	22:54:43·6	18	Z	G	60	abb	− 900
50			19	NS	H	60	aba	
51			20	Z	G	60	aba	
52			21	Z NS EW	G	30	aca	
53			22	Z NS EW	G	60	aba	
54	09–19–39	23:06:58·1	18	Z	G	60	aba	− 900
55	07–30–41	21:39:01·1	18	Z	G	60	abd	−2900
56	07–30–41	21:46:16·6	18	Z	G	60	abd	−2900
57	01–29–43	11:11:43·1	18	Z	G	60	abc	−2900
58	01–29–43	11:13:15·1	18	Z	G	60	aba	−2900
59	03–31–43	11:41:49·1	18	Z	G	60	aba	−2900

In Table IV the alignment of the seismometers is indicated according to the following system. Z indicates a vertical component, NS a horizontal component in which the moving system vibrates in a north-south line and EW a horizontal component in which the moving system is free to move in an east-west line. In one case a seismometer was aligned so as to be free to move in a northeast-southwest direction and this has been designated NE. During the first two summers, the direction of the field stations with respect to Kirkland Lake was such that a NS component was essentially radial to the line joining the station to Kirkland Lake while an EW component was approximately transverse. Thus the NS provided the principal P reading and the EW the principal S reading. During the last summer, the line had deviated so much from a north-south one that the seismometers were set up to be radial (designated R) and transverse (designated T). This was, of course, only approximate since the bursts might occur anywhere along the three miles length of the camp.

Events numbered 43 to 59 date from the earlier program and have already been considered. The latter five of these were timed by the former Kirkland Lake station and the elapsed time of the principal P phase recorded at Ottawa was determined. This travel-time was used to obtain the time occurrence of the earlier bursts. In the earlier work no allowance was made for the distance of the burst from the recording station; moreover the the recorder in use at Kirkland Lake at that time had a paper speed of only 30 mm/min. Bursts 34 and 38 of the present project recorded at Ottawa and provided more accurate data by which to adjust the time of occurrence of the earlier bursts. The observant reader will notice that the times given here for events 43 to 59 differ from those given in the earlier paper.

NOTATION EMPLOYED

The paper will consider the possibility of there being several layers within the crust above the Mohorovičić discontinuity. These layers will be indicated, from the surface downwards, by the numbers 1, 2, 3, etc. applied as subscript to the quantity in question. Quantities dealing with the material below the Mohorovičić discontinuity will be indicated by the subscript n. Thus P_1, S_1 are the direct P and S phases, propagated throughout their course in layer 1, P_2, S_2 are the P and S phases refracted at the first discontinuity and travelling horizontally in the second layer, and so on, for whatever number of layers are being considered at the time. This notation, much simpler than that normally used, is due to Leet. The subscript n has long been used as an indication that the region below the Mohorovičić discontinuity is the normal region of earthquake wave propagation.

We shall also have occasion to refer to the secondary phases which can exist in a layered structure such as the crust. Again Leet's notation will be used. This consists in breaking up a phase into its several straight-line segments and indicating these segments by P or S according to the wave type, with a numerical subscript indicating the layer in which it lies. Thus, for example, P_2 could be written $P_1P_2P_1$ since it consists of a ray in layer 1 from the burst to the bottom of the layer, a ray travelling horizontally in layer 2 and a ray in layer 1 returning to the station. Similarly a phase reflected at the first discontinuity would be P_1P_1 or, if a change of wave type were involved, P_1S_1. Reflected phases will have an even number of component parts refracted phases an odd number.

CORRECTION FOR DEPTH OF FOCUS

All bursts utilized in this investigation had variable and appreciable depth of focus, and the recording stations were at different elevations. Corrections have been applied to reduce observed times to the value they would have had if all bursts and all stations had been at sea level. The method of making the correction is illustrated by the following example.

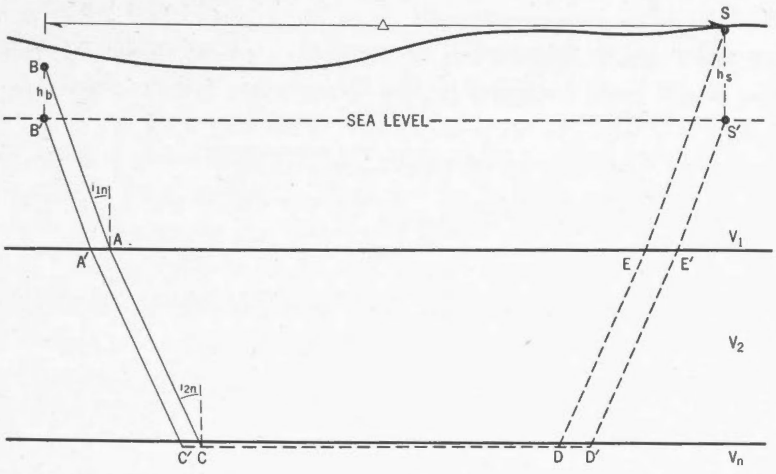


FIGURE 11—Explanation of symbols used in reducing observations to a sea-level datum.

Suppose that we are considering the correction to be applied to P_n in the case of a two-layer crust. The situation is illustrated in Fig. 11 which defines the notation used.

The true path of P_n is BACDES, for which let us suppose the time T to be observed. We wish to assume instead the path B′A′C′D′E′S′ for which the time is say T'. Then the quantity $T' - T$ is a correction to be added to T to yield the required T'. Now

$$T = \frac{BA}{V_1} + \frac{AC}{V_2} + \frac{CD}{V_n} + \frac{DE}{V_2} + \frac{ES}{V_1}, \text{ and}$$

$$T' = \frac{B'A'}{V_1} + \frac{A'C'}{V_2} + \frac{C'D'}{V_n} + \frac{D'E'}{V_2} + \frac{E'S'}{V_1}.$$

Then

$$T' - T = \frac{B'A' - BA}{V_1} + \frac{C'D' - CD}{V_n} + \frac{E'S' - ES}{V_1},$$

since

$$A'C' = AC \quad \text{and} \quad D'E' = DE.$$

Setting

$$B'A' = BA - \frac{h_b}{\cos i_{1n}}$$

$$E'S' = ES - \frac{h_s}{\cos i_{1n}}$$

$$C'D' = CD + h_b \tan i_{1n} + h_s \tan i_{1n},$$

and noting that $\sin i_{1n} = \frac{V_1}{V_n}$, we obtain

$$T' - T = -\frac{h_b + h_s}{V_1} \cos i_{1n}.$$

The same formula applies, with the appropriate velocity, to S_n. It will be noted that the formula does not involve the second layer in any way. Once made, the correction does not have to be changed for various interpretations of the number of layers.

In general, the correction to be applied to reduce observations of P_j or S_j to a sea-level datum is

$$T' - T = -\frac{h_b + h_s}{V_1} \cos i_{1j}.$$

In the case of P_1 and S_1 this system of correction breaks down, for the energy presumably follows the direct path between B and S, and does not penetrate to depth. In this case we compute

$$\Delta' = \sqrt{\Delta^2 + (h_s - h_b)^2}$$

and plot travel times against these distances.

TRAVEL-TIMES AND THEIR INTERPRETATIONS

OUTLINE

The profile to be analysed consists of two sections: a series of fourteen stations lying between 8 and 174 km, and a series of five stations at distances of 451 to 942 km. Two stations intended to fill up the gap between these two groups were operated for about two years without recording a burst. It was necessary to choose between suffering an indefinite delay in the publication of results and proceeding with the analysis without the data from these important stations. Since plans were well advanced for a new program, to be based on explosives and involving improved instrumentation, it seemed pointless to continue the expensive effort necessary to complete the rockburse profile in its final detail.

As it turns out, travel-times of first arrivals out to a distance of 174 km. define a single straight line through the origin. Travel-times of first arrivals at the distant stations define a second straight line which is clearly P_n. The two lines intersect at a distance of approximately 190 km. Thus if a second layer is to be indicated by first arrivals they could only be expected to begin between the 174 km. distance of the most distant field station and the 190 km. point of intersection. Under these circumstances it would certainly indicate itself by secondary arrivals at the more distant of the field stations. The failure to fill up the gap between the two groups of stations is thus not as serious as might at first appear.

In the following analysis we shall first of all discuss the first arrivals of P and the equivalent S phases. A very prominent S phase in the records of the distant stations will then be discussed. These principal phases will lead us to two distinct hypotheses which will then be examined in the light of secondary arrivals and other evidence.

THE PRINCIPAL PHASES P_1, S_1, P_n, S_n.

Description of the Records

Travel times, reduced to a sea-level datum, of the principal phases P_1, S_1, P_n and S_n are listed in Table V.

It will be noted that for P_1 and S_1, entries are limited to the near station data, and that for S_n the data derive solely from the distant stations. In the case of P_n the curve was first defined on the basis of the distant stations, but, since this curve passed through prominent secondary arrivals at distances back to the point of emergence of the critical ray, secondary arrivals from the field stations have been included. A similar procedure could not be followed in the case of S_n because the secondary S arrivals were so confused that no independent selection of phases could be made. It should be mentioned that, while excellent records were obtained at Harvard, the time correction was doubtful. For this reason the P_n time has not been used and the readings of later arrivals have been obtained by adding the phase minus P_n interval to the expected arrival time of P_n. These readings have been placed in parenthesis in Tables V and VI.

The recognition of P_1 is simply a matter of observation since it is the first phase to arrive at stations within about 190 km. of the source. Actually, some difficulty was experienced in identifying P_1 at certain distances. For stations within 50 km. of Kirkland Lake, the first arrival was sharp and simple in character, with no ambiguity as to its precise beginning. The records beyond this point were more complex in their early sections. This was probably due, in part, to the use of Willmore seismometers at most of these stations, although even the Sprengnether seismographs produced records of some complexity. The stations from Hanbury to Fabre showed the first arrivals to be of low amplitude and of relatively long period; this small beginning was followed almost immediately by a large phase and several strong phases were crowded into the first two seconds of the record.

This double beginning at stations between Hanbury ($\Delta = 66$ km.) and Fabre ($\Delta = 120$ km.) is rather unusual and is probably worthy of more detailed documentation. In a typical record, at Hanbury, the record began with a very small disturbance of period

TABLE V

Travel-Times of Principal Phases

Event Number	Δ km.	Δ′ km.	Travel-Times and Residuals—Seconds												
			P_l		P_n					S_l				S_n	
			Travel Time	Residuals Eqn. 1	Travel Time	Residuals Eqn. 3	Residuals Eqn. 4	Residuals Eqn. 5	Residuals Eqn. 6	Travel Time	Residuals Eqn. 2	Residuals Eqn. 9	Residuals Eqn. 10	Travel Time	Residuals Eqn. 7
1	8·83	8·92	1·41	−0·02											
2	8·48	8·53	1·13	−0·24											
3	8·32	8·39	1·29	−0·05						2·49	+0·12	+0·22	+0·14		
4	14·87	14·93	2·36	−0·03						4·04	−0·17	+0·01	−0·14		
5	14·87	14·93	2·46	+0·07											
6	15·00	15·03	2·42	+0·01											
7	24·70	24·73	4·14	+0·18											
8	24·70	24·73	4·26	+0·30						7·54	+0·56	+0·86	+0·62		
9	24·88	24·91	4·05	+0·06						6·73	−0·30	0·00	−0·24		
10	33·32	33·34	5·51	+0·17						9·14	−0·27	+0·13	−0·19		
11	43·89	43·90	6·81	−0·22											
12	43·17	43·18	6·81	−0·10											
13	43·75	43·77	7·01	0·00											
14	43·75	43·77	6·99	−0·02											
15	43·17	43·18	6·82	−0·09											
16	43·17	43·18	6·76	−0·15						11·58	−0·61	−0·08	−0·50		
17	43·17	43·18								12·36	+0·17	+0·70	+0·28		
18	51·38	51·40	8·18	−0·05						14·35	−0·16	+0·47	−0·02		

19	52·02	52·03	8·42	+0·09						14·41	−0·27	+0·36	−0·13		
20	65·86	65·88	10·44	−0·11											
21	66·13	66·13								(18·65)	−0·01	+0·79	+0·18		
23	65·80	65·82								18·44	−0·13	+0·66	+0·06		
25	66·13	66·13								(18·38)	−0·28	+0·52	−0·09		
22	77·13	77·13								(21·52)	−0·25	+0·69	−0·01		
24	76·80	76·80	12·22	−0·08						21·45	−0·22	+0·71	+0·01		
26	77·13	77·13								(21·43)	−0·34	+0·60	−0·10		
27	99·18	99·19	15·80	−0·08	19·84	+0·42		+0·21	+0·33	28·04	+0·05	+1·25	+0·38		
28	99·56	99·56	15·72	−0·22											
40	102·19	102·19	16·36	0·00	19·50	−0·30		−0·50	−0·37	28·72	−0·12	+0·12	+0·23		
29	120·00	120·00	19·11	−0·10											
31	138·64	138·64			24·34	−0·06		−0·12	−0·03	40·41	+1·29	+2·96	+·181		
32	138·64	138·64			24·33	−0·07		−0·13	−0·04						
33	152·43	152·43			25·95	−0·19		−0·19	−0·13	44·37	+1·35	+3·20	+1·96		
34	174·35	174·35	28·04	+0·13	28·9	0·0		+0·1	+0·1	48·7	−0·5	+1·6	+0·2		
38	174·35	174·35			28·8	−0·1		0·0	0·0						
41	174·35	174·35	28·10	+0·19	29·2	+0·3		+0·4	+0·4	48·3	−0·1	+1·2	−0·2		
42	174·32	174·32			29·0	+0·1		+0·2	+0·2						
Mean	451·0	451·0			63·2		+0·4	+0·5	+0·4					108·5	−0·9
50	578·5	578·5			77·5		−0·8	−0·8	−0·9					135·5	−0·2
51	807·5	807·5			107·0		+0·8	+0·7	+0·8					186·9	+4·0
52	919·5	919·5												(203·4)	−2·6
53	942·7	942·7			122·5		−0·2	−0·3	−0·1					210·5	−0·3

0·6 sec. and was followed after an interval of 0·4 sec. by a much larger phase with period of the order of 0·2 sec. The two phases are distinct and do not grade into each other. The small beginning phase is so indistinct that one always had the feeling that, with a little more sensitivity, an even earlier beginning might be read. The foregoing description applies only to the Willmore records; the Sprengnether instruments were too insensitive to record the small initial disturbances. In all cases the earliest possible phase was read.

At Laniel and Shoomagan the only bursts recorded were weak and the small beginning phase was lost. The first visible motion arrived so much later than the expected arrival time of P_1 that it was necessary to conclude that it was not P_1. At Temiskaming P_1 was recorded, but with small amplitude. All these observations suggest that, on this particular traverse at least, P_1 suffers severe attenuation with distances. This is contrary to the findings of Leet[8] who found P_1 to be well recorded at distances of four or five hundred kilometers.

While readings of S phases are never as clear as those of the first arrivals, since they are recorded on an already disturbed trace, there was no difficulty whatever in recognizing S_n at the distant stations and very little difficulty in identifying the first S arrivals at the near station. This phase, of course, was read most accurately on the transverse horizontal components. The observed arrival times are listed in the table. In some few cases readings were admitted from unlocated bursts by adding the S–P interval to the expected travel-time of P_1. These observations have been placed in parenthesis in the table.

Travel-time Equations

The travel-time observations listed for P_1, P_n, S_1, and S_n were now fitted to sets of straight lines each having an equation of the form

$$t = t_o + \frac{\Delta}{V}$$

where t_o the constant term in the equation, will be called the intercept time. The reduction was carried out by least square methods assuming that only the t-observations were subject to error. In an earlier section it was shown that the probable error of a single observation of t was of the order of ± 0·06 sec. For $V = 6{\cdot}24$ km/sec. the corresponding distance error would be approximately ± 0·4 km., or ± 1300 feet. Since the distances are known in most cases to within ± 100 feet the errors in Δ are negligible compared with those in t.

The travel-time equations for P_1 and S_1 proved to be as follows, the uncertainties being probable errors*.

For P_1 $$t = -0{\cdot}03 \pm 0{\cdot}03 + \frac{\Delta}{6{\cdot}234 \pm 0{\cdot}015}$$

For S_1 $$t = -0{\cdot}15 \pm 0{\cdot}15 + \frac{\Delta}{3{\cdot}526 \pm 0{\cdot}021}.$$

Since the probable error of the constant term is in each case of the same order of magnitude as the term with which it is associated it is clear that the constant terms do not differ significantly from zero. Furthermore, retaining a constant term would, in effect, be implying the existence of a thin surface layer. This is not consistent with observation.

---

[8] Leet, L. D. "Velocity of P in the Granitic Layer", *Trans. Am. Geoph. Un.*, Vol. 27: 631–635.

* Except where noted this convention is followed throughout the body of the paper.

Finally, since some of the uncertainty has been absorbed in the absolute term, one obtains an anomalously small value for the probable error of the velocity. Clearly then we should insist on the curve going through the origin.

When this is done the equations become the following:

For P_1 $$t = \frac{\Delta}{6\cdot246 \pm 0\cdot015}, \qquad \ldots\ldots\ldots\ldots\ldots (1)$$

and for S_1 $$t = \frac{\Delta}{3\cdot544 \pm 0\cdot023}. \qquad \ldots\ldots\ldots\ldots\ldots (2)$$

By calculating expected arrival times at each station, and taking the difference between calculated and observed arrival times, it is possible to obtain the probable error of a single time observation. These work out to have the following values:

for P_1 ± 0·09 sec.
for S_1 ± 0·35 sec.

We shall have occasion to refer to these values in a later section.

It will be recalled that in reducing the Kirkland Lake observations to obtain the actual time of occurrence of the bursts it was necessary to use an "appropriate" velocity. Further use of this velocity was necessary in applying the corrections to reduce the observations to a sea-level datum. The velocity employed was that obtained by a preliminary least square solution for the velocity of P_1, 6·20 km/sec. being the actual figure used. This procedure is open to some question since the rocks in the immediate vicinity of the mines are largely metamorphosed sediment rather than granite.

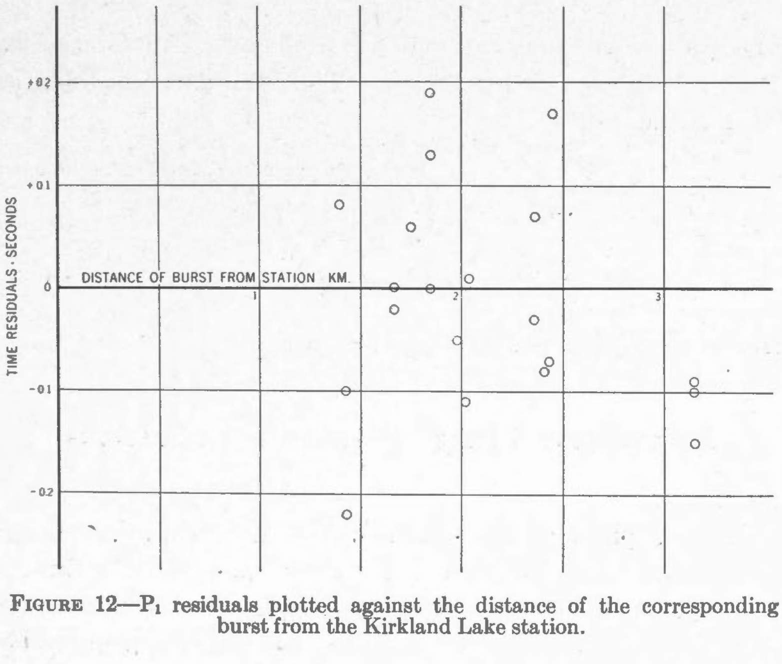


Figure 12—P_1 residuals plotted against the distance of the corresponding burst from the Kirkland Lake station.

An indication that the velocity used was correct within the accuracy of the observations is afforded by the fact that the constant term t_0 in the equation for P_1 was found to be $-0\cdot03 \pm 0\cdot03$, a negligible amount. A further check is obtained by a study of the time residuals in the final P_1 solution. In Fig. 12 these residuals are plotted against the distance of the corresponding burst from the Kirkland Lake station. While the method of reduction would ensure that the algebraic sum of the residuals would be approximately zero, any significant error in the velocity employed would cause them to show some consistent variation with the distance over which the correction had been applied. The distribution of these residuals, as shown by Fig. 12, exhibits no such systematic arrangement. It is therefore concluded that the correction has been properly applied.

The data listed for P_n consist of nine observations at distances between 99 and 175 km., and four observations between 451 and 943 km. Treating these two sets of data separately we obtain the best straight-line fit to the first set as

$$t = 6\cdot89 \pm 0\cdot28 + \frac{\Delta}{7\cdot913 \pm 0\cdot125}, \qquad \ldots\ldots\ldots(3)$$

and for the second set

$$t = 7\cdot86 \pm 0\cdot83 + \frac{\Delta}{8\cdot211 \pm 0\cdot074}. \qquad \ldots\ldots\ldots(4)$$

Combining the two sets of data for a single linear solution one obtains

$$t = 7\cdot50 \pm 0\cdot11 + \frac{\Delta}{8\cdot176 \pm 0\cdot013}. \qquad \ldots\ldots\ldots(5)$$

The variation between these three solutions suggests that a straight line may not be the best fit to the points. If a solution in the form of a parabola is attempted one obtains

$$t = 7\cdot24 + 0\cdot1238\Delta - 0\cdot000{,}001{,}5\,\Delta^2 \ldots\ldots\ldots\ldots\ldots\ldots(6)$$

The probable errors of a single observation of t in each of the four solutions are respectively 0·16 sec., 0·48 sec., 0·28 sec., and 0·28 sec. Thus the parabolic solution is no better statistically than the linear one.

The travel-time equation for S_n has to depend entirely on the five observations at distant stations. The following equation is obtained:

$$t = 16\cdot3 \pm 3\cdot4 + \frac{\Delta}{4\cdot85 \pm 0\cdot10}, \qquad \ldots\ldots\ldots\ldots(7)$$

the probable error of a single time observation being 1·9 sec.

A PROMINENT S PHASE AT THE DISTANT STATIONS

Description of the Records

The most prominent phase on the records of the distant stations lies in the S group, beginning a little earlier than the expected arrival time of S_1. On the short-period Benioff records it is characterized by very large amplitudes continuing for more than a minute. The disturbance is of relatively high frequency and appears to be made up of a large number of phases, each with an impulsive beginning. On the Wood-Anderson records the disturbance is of lower frequency, but again it continues for about a minute and appears to be made up of a number of sharp beginnings. Typical records are reproduced in Fig. 13–15.

When the analysis reported in the earlier paper[2] was carried out, records were available only from Ottawa, Shawinigan Falls and Weston. It was noted that at Weston the apparent beginning of the phase was about four seconds earlier on the vertical record than on the horizontals. A corresponding pair of phases was noted on the Ottawa vertical records. On the basis of intercept time the second of this pair of phases was designated S_2 and ascribed to propagation through an intermediate layer. The earliest arrival was called F, for false S, and was unexplained.

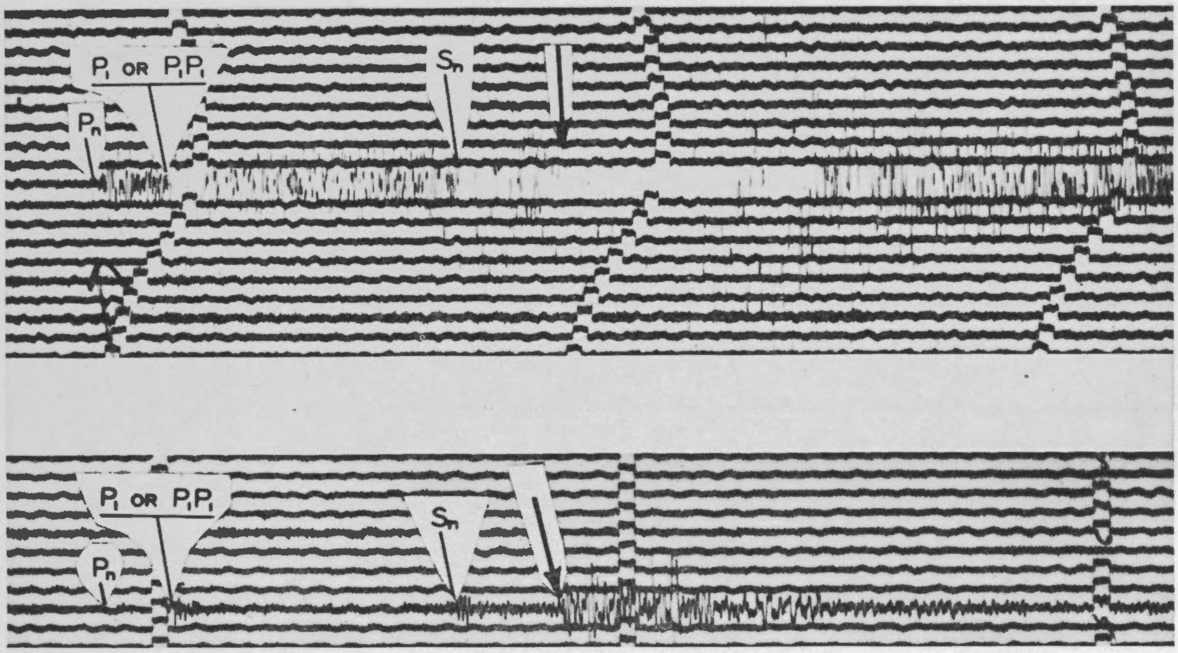


FIGURE 13—Short-period Benioff vertical records obtained at Ottawa ($\Delta = 451$ km.). The upper record is of the same burst which produced the records shown in Figures 14 and 15. The lower record is of a smaller burst and shows more clearly the character of the prominent S phase mentioned in the text. The beginning of this phase is indicated by the heavy arrow.

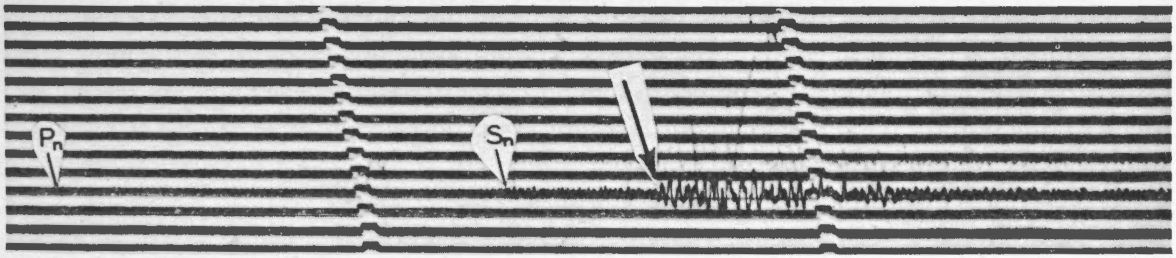


FIGURE 14—The same burst shown in the upper part of Figure 14, as recorded on the Wood-Anderson seismograph at Shawinigan Falls ($\Delta = 578$ km.). The prominent S phase is again indicated by the heavy arrow.

In the preliminary analysis of the present data[9, 10] the same interpretation was considered as one of two alternative hypotheses. Records from Williamstown and from Harvard have since become available and it becomes clear that the distinction made in

---

[9] Hodgson J. H.—"A Seismic Survey in the Canadian Shield", Ph.D. Thesis, University of Toronto, 1951.

[10] Hodgson, J. H.—"Structure de l'Écorce du Bouclier Canadien", *U.G.G.I. Comptes Rendus des Séances de la Neuvième Conférence*, p. 112, abstract only.

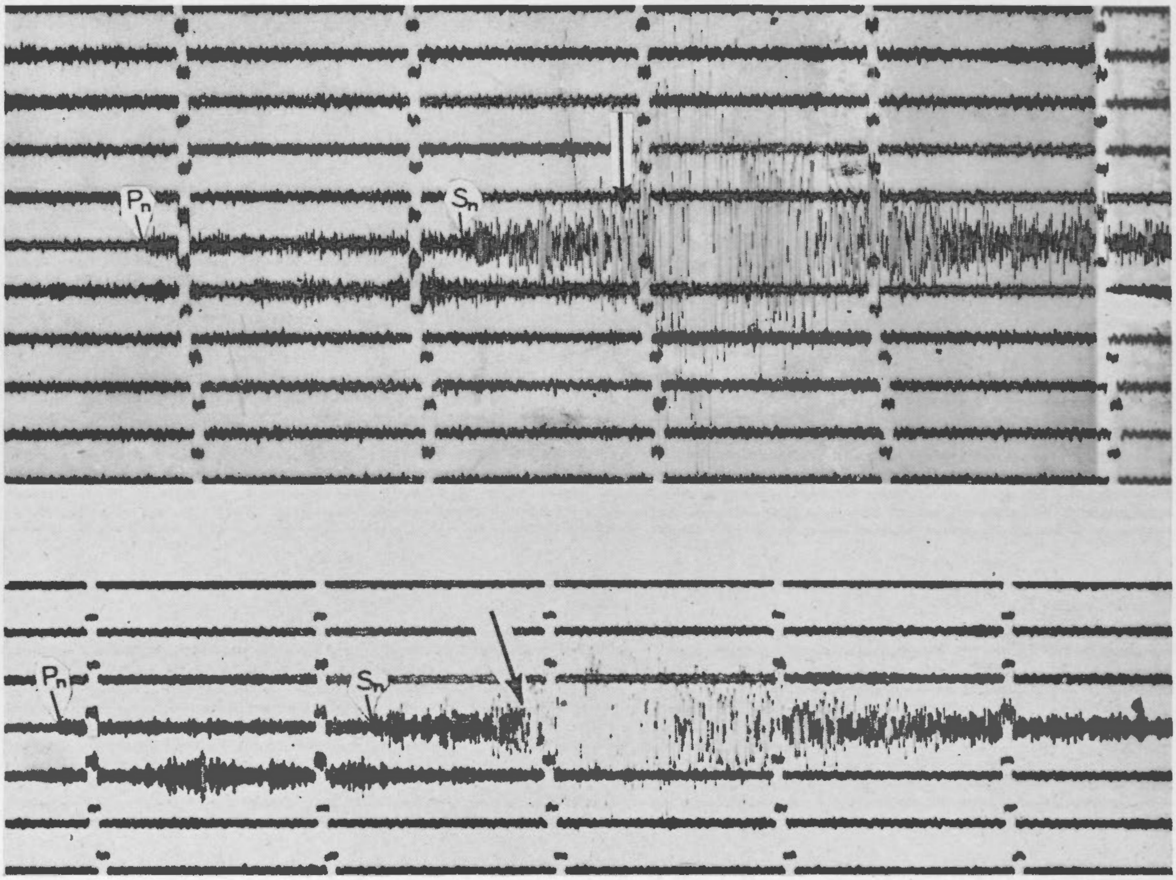


FIGURE 15—Harvard (Δ = 920 km.) records of the same burst shown in Figure 14 and in the upper section of Figure 13. Short-period Benioff seismographs, vertical component above, EW below.

the earlier paper is quite artificial. In fact the beginning of the group is erratic and it is impossible to correlate the several phases in the group from one distance to the next with any certainty. In the present analysis I confine myself to reading the apparent beginning of the large amplitude and seeking an interpretation on the assumption that it actually represents a consistent phase.

TABLE VI

Travel-Times for the Prominent S Phase at the Distant Stations

Station	Event Number	Distance km.	Travel-time sec.	Residuals Eqn. 9	Residuals Eqn. 10
Ottawa	Mean	451·0	121·4	−0·4	−2·4
Shawinigan Falls	50	578·5	155·4	−0·9	−2·3
Williamstown	51	807·5	222·2	+4·1	+4·4
Harvard	52	919·5	(243·2)	−5·2	−3·4
Weston	53	942·7	254·9	+0·3	+2·4

Travel times for this first beginning are listed in Table VI. The parentheses enclosing the Harvard observations are an indication of the uncertainty of the time correction as discussed earlier.

Travel-Time Equations

Least square analysis of the data of Table VI discloses that the best straight line through the points has the equation

$$t = 0{\cdot}9 \pm 4{\cdot}5 + \frac{\Delta}{3{\cdot}73 \pm 0{\cdot}08},$$

with the probable error of a single observation of time having the value 2·5 sec. It is quite clear that the absolute term in this equation has no significance. While it need not necessarily follow that the straight line does go through the origin, the accuracy of the present data do not justify any other assumption. Under this assumption which means abandoning temporarily the hypothesis of a two-layer crust, the equation becomes

$$t = \frac{\Delta}{3{\cdot}71 \pm 0{\cdot}08}, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

the probable error for a single observation of t being 2·6 sec.

Once it is agreed that the straight line must pass through the origin it becomes identified, in our notation as S_1. It becomes necessary to combine the S_1 observations of Table VI with those of Table V. Insisting that the straight line should go through the origin, one obtains its equation as

$$t = \frac{\Delta}{3{\cdot}702 \pm 0{\cdot}011} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

with the probable error of a single time observation having the value of 1·2 sec.

Alternately we might assume that velocity increases with depth throughout the first layer. As a first approach to this analysis the data were fitted to a parabola having the equation

$$t = 0{\cdot}2802\Delta - 0{\cdot}000{,}013\Delta^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

the probable error of a single observation of t proved to be 1·0 sec.; the surface velocity (the inverse of 0·2802) is 3·569 km/sec.

Possible Crustal Structures

This completes the analysis of what we shall call the principal phases. Other phases on the records will be discussed in a later section as secondary arrivals.

Since no phase refracted through a second layer has been indicated by the principal arrivals we must, at this stage, confine our considerations to crusts having a single layer. It may be mentioned however that subsequent study of secondary arrivals will not establish the existence of a second layer, so that the computations of this section are final within the limits of the present paper. We have to distinguish two hypotheses—first that the crust consists of a single layer, statistically homogeneous, second that it consists of a single layer in which the velocity increases as a function of depth.

Single Uniform Layer

Crustal Dimensions.—We may solve by routine methods for the thickness of the layer. For the P waves this involves combining equation (1) for P_1 with either of equations (3) or (5) for P_n. The choice depends on whether we wish to obtain the thickness under the near stations only or the average thickness under the entire profile. By making use of the probable errors given in the travel-time equations one can obtain corresponding uncertainties in the computed thickness, although these are not, strictly speaking, probable errors. Equivalent computations using S waves are carried out by combining equations (2) and (7).

The results of the computations are summarized as follows:

Using P waves	Near stations only:	Thickness = 35·4 ± 5·5 km.
	All stations :	Thickness = 36·4 ± 1·5 km.
Using S waves	:	Thickness = 44·1 ± 14·7 km.

Discussion of these figures is reserved for a later section, but it is worthwhile pointing out that the large uncertainty in the S-determination is a function of the large probable errors in the equation for S_n, while the low uncertainty of the "all station" P-determination is a reflection of the low probable error of the corresponding P_n equation. This in turn has been the result of combining two sets of data corresponding to groups of points widely separated in distance.

Supporting Evidence.—Considerable support is lent to the single layer hypothesis by considering the point of emergence of the critically reflected ray, that is, the point at which P_n first exists*.

Suppose (Fig. 16) that P_n is first observed at a distance Δ; let the thickness of the crust and the average velocity through it be d and $\overline{V}$ respectively, both considered unknown.

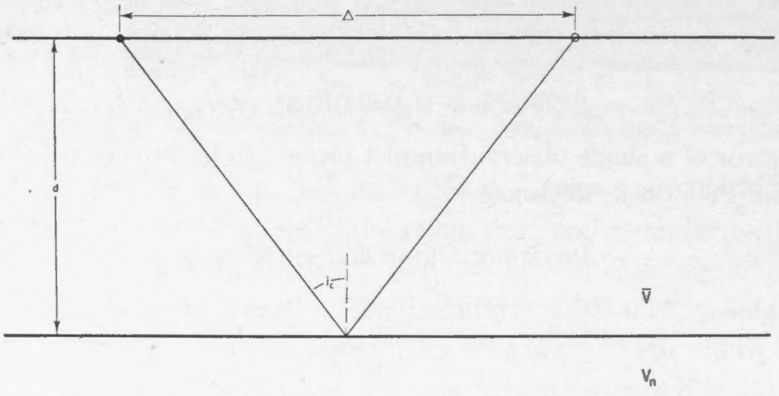


FIGURE 16—Explanation of symbols used in obtaining mean crustal velocity.

Let the time required for P_n to travel the path of total reflection be t, which we shall determine from the travel-time equation. Then, by inspection of the figure we may write immediately.

$$2\,d\,\tan\,i_c = \Delta$$

$$2\,d\,\sec\,i_c = t\,\overline{V}\ ,$$

which, making use of the fact that

$$\sin\,i_c = \frac{\overline{V}}{V_n}\ ,$$

is a system of two equations in the two unknowns d and $\overline{V}$.

---

* I am indebted to Dr. P. L. Willmore for pointing out the efficiency of this test.

In the present case P_n was observed at Ville Marie II ($\Delta = 99$ km.) and was not observed at New Liskeard ($\Delta = 77$ km.). We may then assume the distance of emergence to be 88 ± 11 km. Taking account of both distance and travel-time uncertainties the corresponding travel-time is 18·04 ± 1·85 sec. Carrying through the computations we obtain the following results:

$$\overline{V} = 6\cdot15 \pm 0\cdot22 \text{ km/sec.}$$
$$d = 34\cdot8 \pm 11 \text{ km.}$$

This average velocity $\overline{V}$ agrees very well with the determined value of V_1, 6·246 km/sec. It would be possible of course to have a second layer differing only slightly in velocity from the first, or to imagine a combination of high and low speed beds which would fit the observed average. In a later section, when secondary arrivals are discussed, we shall find further evidence in support of the hypothesis of a single layer. In the meantime we may regard the agreement as encouraging.

Single Layer, Velocity Increasing with Depth

We were led to consider this hypothesis by the fact that equation (10), which fits a parabola to all S_1 data, gave a slightly better fit than the straight line of equation (9). Unfortunately a parabolic equation does not lend itself to studies of the variation of velocity with depth. A method already described by Willmore, Hales and Gane[11] will, therefore, be employed.

The method consists of assuming that the velocity increases linearly with depth, according to a relation of the form.

$$v = v_0 + aZ.$$

Under these circumstances the travel-time equation takes the form

$$t = \frac{2}{a} \sinh^{-1} \frac{a\,\Delta}{2v_0},$$

which, to a sufficient degree of accuracy is approximated to by the first two terms in the expansion, viz:

$$t = \frac{\Delta}{v_0} - \frac{1}{24}\,\frac{a^2\Delta^3}{v_0{}^3}.$$

Dividing through by Δ we obtain

$$\frac{t}{\Delta} = \frac{1}{v_0} - \frac{1}{24}\,\frac{a^2\Delta^2}{v_0{}^3},$$

which may be regarded as a straight line equation relating $\frac{t}{\Delta}$ and Δ^2. Ordinary least square methods may then be applied.

Applying this new method of analysis to the S_1 data of Tables V and VI we obtain the following values

$$v_0 = 3\cdot560 \pm 0\cdot016 \text{ km/sec.}$$
$$\frac{1}{24}\,\frac{a^2}{v_0{}^3} = (0\cdot1589 \pm 0\cdot0443) \times 10^{-7}$$

which, on solution, yield for a the value 0·00415.

---

[11] P. L. Willmore, A. L. Hales, and P. G. Gane, "A Seismic Investigation of Crustal Structure in the Western Transvaal", *Bull. Seism. Soc. Am.* Vol. 42, 53–80, 1952.

Thus the equation governing velocity increase is as follows:

$$v = 3\cdot560 + 0\cdot00415\ Z.$$

Is this rate of velocity increase compatible with the fact that S_1 has been recorded at the distant stations? It may readily be shown that it is not. The depth of penetration Z of a ray emerging at distance Δ is given by the formula

$$Z = \frac{a\Delta^2}{8v_0}\ .$$

The depth of penetration corresponding to the distances of the several stations work out to be the following.

Ottawa	—	29·7 km.
Shawinigan Falls	—	48.9 km.
Williamstown	—	95·2 km.
Harvard	—	123·4 km.
Weston	—	129·7 km.

These values are of course absurd, since rays attempting to penetrate to these depths would have been cut off by a crust of any reasonable dimensions. We need carry the investigation no further, but may discard the hypothesis immediately.

SECONDARY ARRIVALS

Distant Station Records

Description of the Records.—Records from some of the distant stations have already been reproduced in Fig. 13–15. Examination of these records will augment the following description.

Other than P_n, the first arrival, the only P phase prominent in the records of the distant stations is observed at Ottawa at a time very close to the expected arrival time of P_1. This phase is so prominent and is recorded so consistently that it was used in the earlier paper[2] to time bursts which had not been timed at the source. In that earlier paper it was designated P_2. According to the present analysis it might very well be P_1, except for the fact that on the field station records P_1 was badly attenuated with distance. There is considerable inconsistency in supposing P_1 to be small at 150 km. and large again at 450 km.

This inconsistency may be more apparent than real. The stations at Laniel, Shoomogan and Temiskaming lie on the opposite side of the Lake Temiskaming fault system from the bursts, and it is not impossible that energy is being absorbed by local conditions. In any event we have to account for the prominent phase at Ottawa and at the same time recognize that no other secondary P phase exist at the distant stations.

The S phases of the records from the distant stations are much more complex. Between S_n and the prominent phase tentatively identified as S_1 there are several strong phases which, however, do not correlate well from distance to distance. S_1, as we have seen, is simply the beginning of a very prominent group of phases, again apparently quite erratic and incapable of being correlated from one station to the next.

Listing of Possible Phases.—We shall now examine what phases may be called upon to explain these secondary arrivals. In listing possible phases we recall that either a P or S wave, upon striking an interface, gives rise to reflected and refracted phases of both types. The travel-time curves are computed by the application of Snell's Law, making use of the velocities determined by the principal refracted phases. For certain cases the velocities are such that the sine of the angle of incidence is greater than unity, indicating that the phase in question is not geometrically valid.

In the case of a single-layered crust the following phases can exist. The notation has been defined earlier.

P_1P_1
S_1S_1
$P_1S_1 = S_1P_1$

$P_1P_nP_1 \equiv P_n$
$S_1P_nP_1 = P_1P_nS_1$
$S_1P_nS_1$
$S_1S_nS_1 \equiv S_n$

While we have had to abandon temporarily the hypothesis of a second layer, we shall wish to examine the secondary arrivals in the light of this possibility. If we admit a two layer crust, many additional phases become available.

The following is the list of the refracted phases having geometrical validity.

$P_1P_2P_1 \equiv P_2$
$P_1P_2S_1 = S_1P_2P_1$
$S_1P_2S_1$
$S_1S_2S_1 \equiv S_2$
$P_1P_2P_nP_2P_1 \equiv P_n$

$P_1P_2P_nP_2S_1 = S_1P_2P_nP_2P_1$
$P_1P_2P_nS_2P_1 = P_1S_2P_nP_2P_1$
$P_1P_2P_nS_2S_1 = S_1S_2P_nP_2P_1$

$P_1S_2P_nP_2S_1 = S_1P_2P_nS_2P_1$
$P_1S_2P_nS_2P_1$
$P_1S_2P_nS_2S_1 = S_1S_2P_nS_2P_1$
$P_1S_2S_nS_2P_1$
$P_1S_2S_nS_2S_1 = S_1S_2S_nS_2P_1$
$S_1P_2P_nP_2S_1$
$S_1P_2P_nS_2S_1 = S_1S_2P_nP_2S_1$
$S_1S_2P_nS_2S_1$
$S_1S_2S_nS_2S_1 \equiv S_n$

For phases involving reflection there are the following valid possibilities:

P_1P_1
$S_1P_1 = P_1S_1$
S_1S_1

$P_1P_2P_2P_1$
$P_1P_2P_2S_1 = S_1P_2P_2P_1$
$P_1P_2S_2P_1 = P_1S_2P_2P_1$
$P_1P_2S_2S_1 = S_1S_2P_2P_1$

$P_1S_2P_2S_1 = S_1P_2S_2P_1$
$P_1S_2S_2P_1$
$P_1S_2S_2S_1 = S_1S_2S_2P_1$

$S_1P_2P_2S_1$
$S_1P_2S_2S_1 = S_1S_2P_2S_1$
$S_1S_2S_2S_1$

The above list of phases is based upon considerations of geometrical optics only, without any attention being paid to the amount of energy which the various phases might be expected to carry. It was mentioned in the introduction that the classical theory is inadequate to account for the energy carried by the critically refracted phases. It appears however, to give trustworthy results for rays not nearly parallel to the discontinuities.

Gutenberg[12] has carried out an elaborate investigation to determine coefficients of reflection and refraction under various conditions existing in the crust. He re-examined critically all published lists of these coefficients and calculated others. From these data he plotted sets of curves which show, for varying angles of incidence, the energy carried by the several phases set up when an incident ray strikes a discontinuity. He has himself summarized the conclusions in the following words.

"1. If a wave starts out as a P wave, at a reflection or refraction at an internal discontinuity, usually too little energy is transmitted into an S wave to produce an outstanding phase in the seismogram. However, an original S wave may loose more than 90 per cent of its energy at a refraction into a P wave, and yet under favourable circumstances, may produce an impulse exceeding those in the direct P waves.

"2. In waves reflected at internal discontinuities, the resulting amplitudes are often relatively small at the shorter distances, then increase when the critical angle for total reflection is approached, but decrease later . . . . when the angle of incidence of the reflected wave approaches 90°; this latter decrease is most rapid for a change from an incident S wave into a reflected P wave".

Applying Gutenberg's first rule we may delete from the foregoing list all phases in which a P-segment is transformed into an S-segment. The following phases remain:

for a single layer crust,

P_1
S_1
P_1P_1
S_1S_1
S_1P_1
$S_1P_nP_1$
P_n
S_n

and for a two layer crust,

P_1
S_1
$P_1P_2P_1 \equiv P_2$
$S_1P_2P_1$
$S_1S_2S_1 \equiv S_2$
$S_1P_2P_nP_2P_1$
$S_1S_2P_nP_2P_1$
P_n
S_n

P_1P_1
S_1S_1
S_1P_1
$P_1P_2P_2P_1$
$S_1P_2P_2P_1$
$S_1S_2P_2P_1$
$S_1S_2S_2P_1$
$S_1S_2S_2S_1$

Let us now consider the form of the travel-time curve for these phases at the distant stations. P_1P_1 and S_1S_1, reflections at the base of the crust of P and S waves, have a travel time curve practically identical with P_1 and S_1 at great distance. For this reason the prominent P phase at Ottawa may satisfactorily be ascribed to P_1P_1. It might be thought that S_1P_1 would arrive about midway P_1P_1 and S_1S_1 but, in fact, because of the geometry involved in applying Snell's law, the S section is very short and P section very long. At the larger distances it arrives only a few seconds after P_1. Similarly $S_1P_nP_1$ arrives only a few seconds after P_n. Clearly then a single layered crust does not satisfactorily account

---

[12] Gutenberg, B.—"Energy Ratio of Reflected and Refracted Seismic Waves", *Bull Seism. Soc. Am.*, Vol. 34; 85–101, 1944.

———————— — "Reflected and Minor Phases in Records of Nearby Earthquakes in Southern California", *Bull. Seism. Soc. Am.*. Vol. 34; 137–160, 1944.

for the observed phases, for it produces secondary arrivals in the P group where they are not in fact observed, rather than in the S group as required. The situation is not much better in the case of a two layer crust. We have the new phase P_2, followed closely by $S_1P_2P_1$, $P_1P_2P_2P_1$, $S_1P_2P_2P_1$, and $S_1S_2P_2P_1$, and the new phase S_2 associated closely with $S_1S_2S_2P_1$ and $S_1S_2S_2S_1$, producing one group in the desired range. Of the remaining phases $S_1 P_2 P_n P_2 P_1$ and $S_1 S_2 P_n P_2 P_1$ arrive very shortly after P_n, while $P_1 P_1$ and $S_1 P_1$ arrive with P_1, and $S_1 S_1$ with S_1. By introducing a second layer we are able to account only for one additional group of phases in the S section. If we are to account for the complexity of phases between S_n and S_1, by this method we shall have to introduce a formidable number of layers.

The close grouping of reflected and transformed refracted phases with the principal phases comes about because of the large distances involved. They are much better separated at shorter distances. Thus any decision for an increased number of layers will have to be made from the records of the field stations. We now turn our attention to this matter.

Near Station Records

Description of the Records.—The complexity of the records at the near stations can best be described by showing an actual example. In Fig. 17 the three components of a burst recorded at Fabre (Δ = 120 km.) are reproduced. This record is typical in its complexity, although its amplitude is much larger than average. It will be noted that while the beginnings of P and S are relatively clear there are numerous other phases crowded into each group. It is this complexity which we now seek to explain.

Preliminary Investigation.—If one is willing to accept the simple hypotheses on which the theory is based, then the identification of secondary arrivals is a straight-forward if tedious task. Assuming a single layered crust, travel-time curves of all possible phases can be computed and observed phases checked against these for identification. Recalling that a second layer may possibly be indicated only by secondary arrivals, a sequence of phases may be selected as representing the refracted phase and corresponding travel-time curves drawn for the two layer crust. These again are checked against the remaining observed phases.

In the earlier papers on the present work [9, 10] it was reported that this sort of analysis had been attempted repeatedly but without success, and it was impossible to select between a single- and double-layered crust. Indeed it appeared that a large number of layers would have to be introduced if one was to account even quantitatively for the phases observed.

Reconsideration of the Data.—This state of affairs seemed most unsatisfactory and repeated attempts were made to improve it. It was finally realized that the demands being made on the data were too restrictive and a new hypothesis, as outlined below, was developed.

Examination of a geological map of the Canadian Shield will show that, instead of being a uniform layer as assumed in theory, the area is actually an accumulation of rocks of many types. All varieties of igneous rocks are present, along with metamorphosed sediments having origins of many sorts. It seems very reasonable to suppose that this variation of rock type will provide alternate paths for energy and that the first arrival, read as P_1, corresponds simply to that path having the shortest Fermat path. Any other minimum path should produce a phase. In the same way we can explain a good deal of the complexity in the S group; specifically this explanation may account for the large number of phases in the S_1 group at the distant stations.

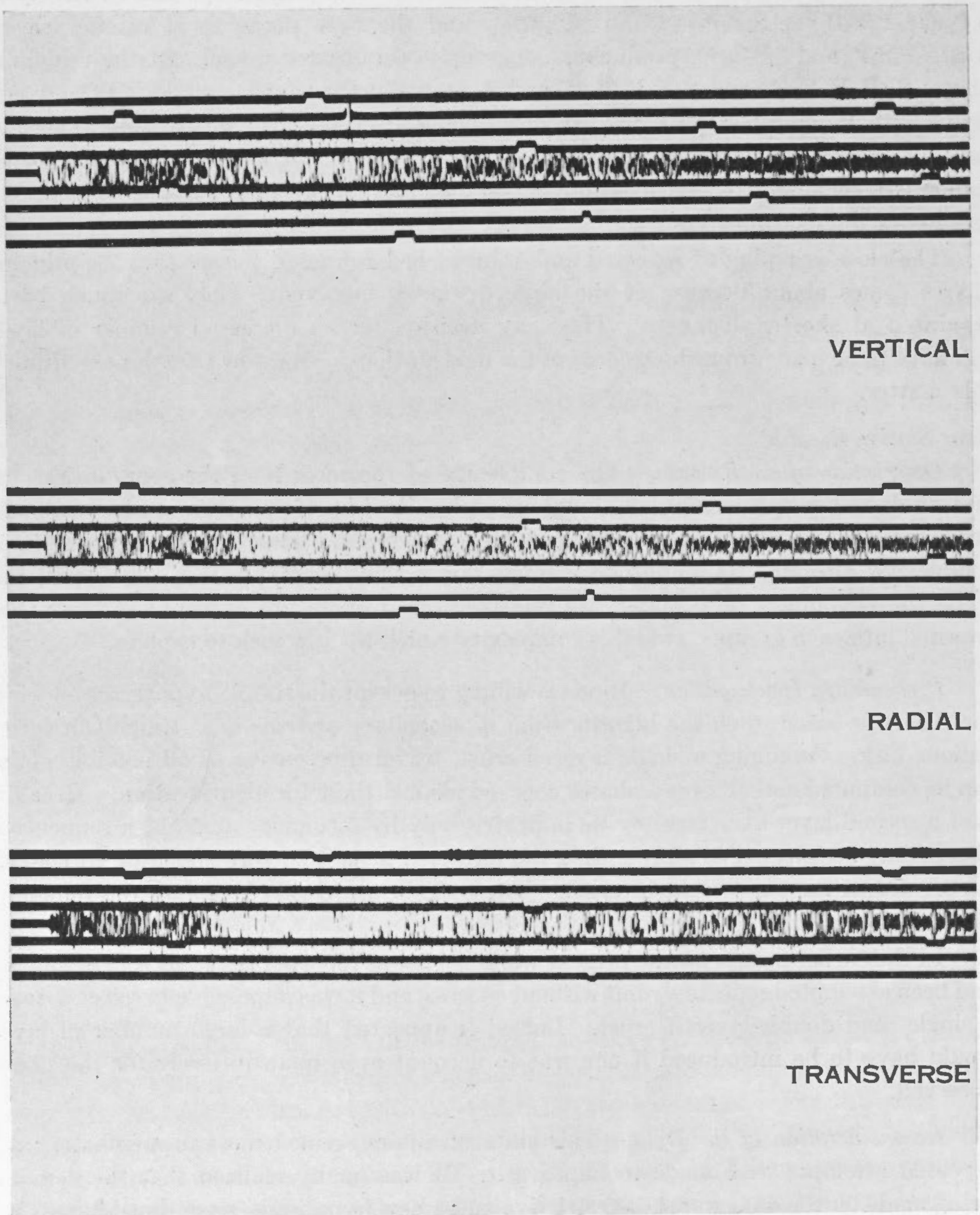


FIGURE 17—The three components of a burst recorded at Fabre (Δ = 120 km.). These records are of larger amplitude than normally obtained but illustrate the normal complexity of the records.

If one is prepared to admit this possibility as reasonable, which can scarcely be denied in the face of the geological evidence, then one must admit a corresponding complexity in the travel-times of secondary phases, for the variations in rock type must extend to some considerable depth and so influence the entire travel-time picture. There is here, however, an additional complication. Our best determination of crustal thickness showed an uncertainty of ± 5 km approximately. This uncertainty appears to be due to uncertainties in time measurements but may these not be due to actual variations in crustal thickness? There is strong evidence from gravity measurements that they are. Garland [13] has analyzed the regional gravity anomalies in a section of the Canadian Shield which includes the present traverse. In this analysis he assumes a two-layer crust as given by the present author in an earlier paper[2] and concludes that a variation of about ± 5 km. at the base of the granitic layer is necessary to account for the observed gravity variations. In a paper now in preparation, Innes[14] will show that the observed gravity anomalies may be attributed to variations at the base of the granitic layer or at the base of a single-layered crust, or to a combination of the two variations, but again the magnitude required is of the order of ± 5 km. It seems probable then that several minimum paths might be provided for reflected waves by the undulating base of the crust and that variations of the order of ± 1 second in arrival time might be explained in this way.

To summarize then, we shall adopt as a working hypothesis that the crust consists of a single layer of variable properties and of variable thickness so that a variety of possible paths are provided for any phase. We will, therefore, expect that phases will appear not singly, but in groups, and we shall attempt to account for groups of energy without insisting on a precise fit to computed travel-time curves.

On the basis of this hypothesis it is concluded that the observed phases are adequately accounted for by a single layered crust. The following remarks in which the several phases are discussed in turn, are simply an amplification of this statement. Once it had been accepted that the data would not support the hypothesis of a two-layer crust, travel-time curves were computed for the single layer crust having the dimensions determined by the P wave data. The comparisons mentioned in the following remarks were with these curves.

The direct phase, P_1, has already been described. Beyond 50 km. its beginning is complex while beyond 120 km. it appears to be severely attenuated. This may well be due to local conditions. Between P_1, and the next travel-time curve there exist, to the distance of Fabre (120 km.) at least, numerous phases, in one or two cases larger than the initial group. They do not appear to define a system of straight lines nor indeed any reasonable curve. In general the number of phases observed decreases with distance. It appears most reasonable to attribute them to rays travelling minimum paths provided by lateral geologic variations. This conclusion is supported by the fact that the P-activity on the transverse component is about as large as that on the radial, showing that the waves have not followed the direct path.

---

[13] Garland, G. D.—"Interpretations of Gravimetric and Magnetic Anomalies on Traverses in the Canadian Shield in Northern Ontario", *Publications of the Dominion Observatory*, Vol. XVI, No. 1, 1950.

[14] Innes, M. J. S.—"Gravity Anomalies in the Canadian Shield", *Publications of the Dominion Observatory*, in preparation.

P_n is observed as a secondary arrival at all stations from Ville Marie II to Temiskaming. In most cases it is a prominent phase, in many instances the most prominent in the P group. It is particularly clear on the Sprengnether records at Ville Marie I and Temiskaming, and was read at these stations as a principal phase some two years before any attempt was made to identify it.

If we admit that the base of the crust, being undulating, should provide a number of minimum reflection paths, then the phases reflected with change of wave form—$P_1 S_1$ and $S_1 P_1$—need not arrive simultaneously. On the simple Sprengnether records at Ville Marie II and Temiskaming we find that $P_1 P_1$ and $P_1 S_1$ occur as sharp beginnings exactly as forecast by the travel-time curves but on the more complicated Willmore records we have to recognize them as energy groups rather than as distinct phases. With this limitation they may be recognized at all stations from Earlton ($\Delta = 50$ km.) to Temiskaming ($\Delta = 174$ km.). They increase in prominance as the critical angle is reached and continue large beyond that point; in particular $P_1 P_1$ forms the largest amplitude in the P group at Shoomogan ($\Delta = 152$ km.).

The direct phase S_1 does not have as clear-cut a beginning as has P_1, and at all distances beyond Earlton ($\Delta = 50$ km.) it marks the beginning of an extremely complex section of the record, the worst complexity lasting about ten seconds. A good deal of this complexity may undoubtedly be explained under our hypothesis, but in addition S_n and $S_1 S_1$ should arrive within this section of the record. These several complications appear adequate to account for the complexity of this S-group but no definite identification of phases has been possible. Ewing and Press* have suggested that the phase $S_1 S_1$ should be well-recorded at normal incidence and have, in addition, asked that a search be made for an S reflection from a depth of approximately 80 km. Examination of the records has failed to produce any observations of the 80 km. reflection; of course when the travel-time curve lies in the disturbed S group mentioned earlier, phases could arbitrarily be assigned to it. $S_1 S_1$ does appear to be recorded, although its arrival times are somewhat erratic, but only as the critical angle is approached and exceeded. There is no indication of it at or near to normal incidence.

For the sake of completeness, mention may be made of the few observations which appear beyond question to be surface waves. These were recorded only on the Sprengnether-Moll combination (system C of Table I). At Earlton ($\Delta = 50$ km.) there was a very well-developed sinusoidal wave on the vertical showing three complete waves as follows:

Velocity	2·87,	2·78,	2·71	(km/sec.)
Period	0·61,	0·43,	0·35	(sec.)

where the velocity is obtained by dividing the total distance by the elapsed time to the beginning of the wave. At Temiskaming ($\Delta = 174 \cdot 4$ km) it was difficult to measure period but the earliest surface wave arrived on the EW with a velocity of 3·45 km/sec.; a second one appeared on the NS with a velocity of 3·14 km/sec. These scattered observations do not seem sufficient to warrant any computations.

---

* Personal communication.

SUMMARY

It is concluded that, under the hypothesis that the crust consists of a single heterogenous layer of variable thickness, it is possible to account quantitatively for the principal features of the seismograms at all distances. It is further concluded that reflected phases do not begin to appear until the critical distance is approached.

Mean values for this heterogeneous crust are as follows, where V, v indicate P, S velocities respectively and σ is Poisson's ratio.

$$\begin{aligned}
V_1 &= 6{\cdot}246 \pm 0{\cdot}015 \text{ km/sec.}\\
v_1 &= 3{\cdot}544 \pm 0{\cdot}023 \text{ km/sec.}\\
\sigma_1 &= 0{\cdot}26 \pm 0{\cdot}02\\
V_n &= 8{\cdot}176 \pm 0{\cdot}013 \text{ km/sec.}\\
v_n &= 4{\cdot}85 \pm 0{\cdot}10 \text{ km/sec.}\\
\sigma_n &= 0{\cdot}24 \pm 0{\cdot}08\\
d &= 36{\cdot}4 \pm 1{\cdot}5 \text{ km}
\end{aligned}$$

The uncertainties of the velocities are probable errors, those on the σ's and d are the results of using probable errors in the velocities as limits in computing these quantities. It is interesting to note the high uncertainty in the determination of Poisson's ratio in the two cases, despite the relatively high accuracy in the determination of the velocities. This would suggest that the arguments sometimes based on the variation of this quantity are not as dependable as might be supposed.

DISCUSSION OF THE RESULTS

PROBABLE ERRORS OF THE OBSERVATIONS

It was shown in an earlier section that errors due to uncertainty of time correction and to error in reading a precise event, such as the first arrival of energy, would lead to a probable error of 0·06 sec. for a single observation of elapsed time. It was suggested that if, after the reduction of all observations, the probable error of a single event proved to be substantially greater than this, it would be an indication of the effect of local conditions. The only phase to which this may be strictly applied is P_1, and here we obtained a probable error of 0·09 sec. for a single observation. The difference is not sufficient to be significant.

The inference to be taken is that the first phase to arrive has travelled at a depth greater than the Keewatin lavas and the Palaeozoic sediments, which form part of the surface rocks along the traverse, and so is propagated in material of more nearly uniform velocity. Later arrivals may have traversed the superficial rocks, either in the line of the traverse or to the side of it. The Palaeozoic sediments are only a few hundred feet thick[15] and the thickness of the Keewatin lavas has been estimated [13] to be of the order of 5000 feet so that it is not surprising that their effect is not noted in the travel-time of the first arrival. In the second paper of this series we shall see that, where the surface rocks extend to depth, they do exercise an appreciable effect on the travel-times.

---

[15] Hume, G. S.—"The Palaeozoic Outlier of Lake Temiskaming, Ontario and Quebec", Geological Survey of Canada, Memoir 145, 1925.

The time residuals for P_n, S_n and the near station data on S_1 are substantially greater than those for P_1. This is to be expected since they derive in most cases from secondary arrivals. The estimated error of 0·06 sec. for the reading of a single observation cannot be applied to such phases. In a general way it would appear to be reasonable to assign the near station S_1 residual entirely to reading error. The larger P_n and S_n residuals probably reflect the variations in crustal thickness.

The residuals for the S_1 reading at the distant stations are much too large to be accounted for on this basis. Discussion on this point is reserved to the following section.

The Prominent S Phase at the Distant Stations

This prominent phase, the beginning of which has been identified as S_1, remains one of the unsolved problems of the research. The large residuals suggest that its beginning is very erratic and it has been impossible to correlate phases within the group with any certainty. One possible explanation is that S_1 is propagated to large distances with such small loss of amplitude that propagation by a large variety of paths is possible. There is some inconsistency here for we have seen that P_1 suffers severe attenuation witb distance. Why then should S_1 be propagated without loss? Furthermore the indicated velocity at the distant stations, 3·71 km/sec., is substantially larger than the 3·54 km/sec. shown by the near station records. This would at first lead us to assume an increase of velocity with depth but since this hypothesis has proved to be untenable we must suppose that velocities in the vicinity of Ottawa and beyond are higher than in the Canadian Shield. This is not a very reasonable assumption and the entire explanation is most unsatisfactory. Another possible explanation has been offered by the L_g phase of Ewing and Press[16]. They have found that small distant earthquakes produce short period surface waves of both Love and Raleigh type. These are of much greater amplitude than might reasonably be expected, but exist only when the path traversed is almost entirely continental. They have designated them L_g and R_g, intending to imply by the subscript g that they are wave-guided in a granitic crust. A recent rockburst at Kirkland Lake has produced a phase at Palisades, identified by them as L_g, which in the notation of this paper is clearly S_1. In other words, their L_g and our S_1, are the same phase at a distance of 1000 km. It should be mentioned that both curves have been extrapolated somewhat, for they had not previously observed L_g at so short a distance.

According to the classical theory Love waves do not have a vertical component and this would appear to offer a serious objection to the interpretation. Press and Ewing have discussed this matter in the reference already cited and are satisfied that, under their postulate of an incompetent layer at the base of the crust, a strong vertical component might be expected. Dr. Press, who has been good enough to read the present paper in manuscript, regards our high velocity of 3·71 km/sec. compared with their velocity of 3·51 km/sec. as a more serious inconsistency. He suggests that their value might be higher if periods of less than say one second could get through over the range they have studied.

In their theory the wave is to be regarded as a superposition of the several modes provided by multiple internal reflections within the surface layer, and this might be an

---

[16] Press, F., and Ewing, Maurice—"Two Slow Surface Waves Across North America", *Bull Seism. Soc. Am.*, Vol. 42, 219–228. 1952.

TABLE VII

		North Germany		Western Transvaal		Wisconsin	Central Appala-chians	Central Atlantic Coastal Region U.S.A.	Canadian Shield
		Willmore[17]		Willmore, Hales and Gane[11]		Slichter[18]	Adams, Tuve and Tatel[19]		
		Single Layer*	Two Layer	Single Layer*	Two Layer	Single Layer	Single Layer	Single Layer	Single Layer
Sedimentary Layer	P Velocity, km/sec.	4·4	4·4	5·65	5·65	4·2 – 4·6	—	—	—
	S Velocity, km/sec.	—	—	3·37	3·37	—	—	—	—
	Thickness, km., from P	6·7	5·9	4·5	4·5	0·6 – 2·8	—	—	Absent
First Layer	P Velocity, km/sec.	5·95	5·57	6·09	6·09	6·0 – 6·9‡	6·0 – 6·7‡	6·1	6·25
	S Velocity, km/sec.	—	—	3·68	3·68	—	—	—	3·54
	Thickness, km., from P	20·7	8·3	29·7	18·2	37 – 43	40 – 50	33	35
Second Layer	P Velocity, km/sec.	....	6·50	....	6·83	....	....	....	....
	S Velocity, km/sec.	....	—	....	3·89	....	....	....	....
	Thickness, km., from P	....	15·7	....	15·5	....	....	....	....
Material below the Mohorovičić Dis-continuity	P Velocity, km/sec.	8·18	8·18	8·27	8·27	8·17	8·06	8·1	7·91–8·21‡
	S Velocity, km/sec.	—	—	4·83	4·83	—	—	—	4·85
	Depth to discontinuity, km.	27·4	29·9	34·2	38·2	40 – 44	40 – 50	33	35

* Preferred Interpretation

‡ Velocity Increasing with Depth

[17] Willmore, P. L. "Seismic Experiments on the North German Explosions, 1946 to 1947", *Philosophical Transactions of the Royal Society of London*, Series A, No. 843, Vol. 242, 123–151.

[18] Slichter, L. B. "Crustal Structure in the Wisconsin Area", Report to ONR, October 31, 1951 (contract N9 onr — 86200.)

[19] Adams, L. H., Tuve, M. A., and Tatel, H. E., "Seismic Exploration of the Earth's Crust", *U. G. G. I. Comptes Rendus des Seances de la Neuvieme Conference*, pp. 113–114.

explanation of the erratic beginning and form of our S_1. At 1000 km. we may be in the range where L_g had not been completely formed, so that the several modes would appear discretely; the erratic nature of the record being explained by the variations in crustal thickness already postulated.

One other point should be mentioned in connection with the phase L_g. In order to account for the large amplitude of the phase, Ewing and Press have postulated that the base of the crust should have a very high reflection coefficient, so high as to ensure the recording of S_1S_1 at normal incidence. This has not been observed; as we have seen it becomes apparent only as the critical angle is reached. The Dominion Observatory proposes to do further research on this point by setting up a Willmore-Watt three-component seismograph at the Kirkland Lake Station. At one point in the development of their theory Ewing and Press suggested that a reflection from 80 km. might also be expected It has already been pointed out that this was not observed at any distance.

It is concluded that, while the properties of L_g appear to account for most of the properties of the phase in question, more work must be done before the identification is positive.

COMPARISON WITH OTHER RESEARCH

The research here described has been contemporaneous with studies in Europe, South Africa and the United States. It will be worthwhile to compare our results with those of these other studies. This comparison is provided by Table VII.

CONCLUSIONS

The data considered in this paper support the following conclusions.

1. The crust in the Canadian Shield is probably single-layered, and heterogeneous in the sense that it is made up of many sorts of rocks. If a second layer is present its velocity cannot differ very much from that in the surface layer. There is no indication of an increase of velocity with depth.
2. The crust has a mean thickness of about 35 km. within the Shield area, but the thickness may vary by as much as 5 km. from this mean value.
3. The Mohorovičić discontinuity is apparently sharp enough to provide reflection of both P and S waves close to the critical angle of incidence, but is not sufficiently abrupt to give reflection at normal incidence.
4. There is no evidence of reflection from a discontinuity at 80 km.
5. The velocities in the crust and in the sub-crustal materials are, with probable errors:

$$V_1 = 6{\cdot}246 \pm 0{\cdot}015 \text{ km/sec.}$$
$$v_1 = 3{\cdot}544 \pm 0{\cdot}023 \text{ km/sec.}$$
$$V_n = 8{\cdot}176 \pm 0{\cdot}013 \text{ km/sec.}$$
$$v_n = 4{\cdot}85 \pm 0{\cdot}10 \text{ km/sec.}$$

6. The appearance of the records at the distant stations, in that part following the expected arrival of S_1, has not been satisfactorily explained.

ACKNOWLEDGMENTS

The program here discussed has been going on for so long and has embraced so many fields of physics and geophysics that the author has become indebted to most of his former colleagues at the University of Toronto and to the present ones at the Dominion Observatory. To all who have assisted he tenders his sincere thanks.

The program was instituted on the recommendation of the Associate Committee of Geodesy and Geophysics, National Research Council, under the chairmanship of Prof. J. T. Wilson. It was brought to the attention of that Committee through the efforts of Prof. Wilson and of the late Prof. E. F. Burton. The work was initially sponsored jointly by the National Research Council, the Dominion Observatory, and the University of Toronto. After the first year it was supported solely by the Dominion Observatory.

During the life of the project the author has been greatly indebted to Mr. R. Meldrum Stewart, former Director of the Dominion Observatory and to Dr. C. S. Beals, his successor. Each has taken a keen interest in the project and assisted it by all possible means. The work was carried out under the immediate supervision of Dr. E. A. Hodgson, former Chief of the Seismological Division, Dominion Observatory, and indebtedness to him is implicit in all that is here written. A special note of thanks is due to Mr. W. G. Milne of the Seismological Division, Dominion Observatory, who has assisted in innumerable ways throughout the survey.

The project would not have been possible without the close co-operation of the managers of the mines at Kirkland Lake. The co-operation has been excellent throughout and our gratitude is correspondingly great. The Hydro-Electric Power Commission of Ontario has assisted in the installation of the stations, on their property, at La Cave and Rolphton.

The very great assistance of the Geodetic Survey of Canada, described in the text, is gratefully acknowledged.

The work has depended upon the close and able co-operation of the operators of the winter stations—F. J. Hallick at Kirkland Lake, G. Montpetit at Ville Marie, F. G. MacLeod at Temiskaming, T. J. Dwyer at La Cave and J. Simpson at Rolphton; and upon the help of the several students who have assisted during one or more of the four summer seasons. These are P. C. Bremner, D. M. Wagg, G. C. Alvey, R. Bergeron, F. Lombardo and D. Dunlop.

It has been a great privilege to discuss the progress of the work with Dr. E. C. Bullard, with Prof. J. Coulomb of the Institut de Physique du Globe, University of Paris, with Dr. P. G. Gane, of the University of Witwatersrand, Johannesburg, and with Dr. P. L. Willmore, formerly of Cambridge University, who has recently joined the staff of the Dominion Observatory. These discussions have been most helpful. Finally, we are indebted to Dr. Bullard and to Dr. Willmore for permission to adapt the Cambridge seismometer to our purposes.

The figures have been drawn in the Map Compilation and Reproduction Section, Surveys and Mapping Branch, Department of Mines and Technical Surveys. I am much indebted to Mr. W. H. Miller, Director of the Branch, for this courtesy.

CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
DOMINION OBSERVATORIES

PUBLICATIONS

OF THE

Dominion Observatory

OTTAWA

VOL. XVI No. 6

A SEISMIC SURVEY IN THE CANADIAN SHIELD

II: Refraction Studies Based on Timed Blasts

BY

JOHN H. HODGSON

EDMOND CLOUTIER, C.M.G., O.A., D.S.P.
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
OTTAWA, 1953

TABLE OF CONTENTS

A Seismic Survey in the Canadian Shield
II: Refraction Studies Based on Timed Blasts

ABSTRACT

During the rockburst studies, described in Part I* of this series, blasts timed at their source were recorded at one or more of the stations of the profile.

One group of blasts, at La Cave and at Rolphton, were timed automatically by the stations maintained at those points. These blasts frequently recorded at the other station of the pair, and sometimes at Ottawa. Timing and location were not as precise as in other sections of this work, but it was possible to determine mean velocities for P_1 and S_1 of 6·29 ± 0·04 km/sec. and 3·44 ± 0·03 km/sec. respectively. The uncertainties listed are Probable Errors of the means.

A second group of blasts, occurring at La Cave and at Temiskaming, were precisely located and were timed with the greatest possible accuracy. They were recorded at stations lying northwestward toward Kirkland Lake, and the series thus provided a reverse profile. P_1 and S_1 velocities obtained, with probable errors, were 6·19 ± 0·07 km/sec. and 3·54 ± 0·07 km/sec. A very strong phase, both in the P and S group, suggested the existence of a second layer, but this interpretation proved to be inconsistent with the evidence of other secondary arrivals.

The final group of blasts provided data on the variation of velocity with rock type. The source was near Sudbury and as the blasts were recorded at eight different stations of the rockburst profile a variation of 47° of azimuth was obtained. This provided many different sections across the Huronian basin. Mean velocities, and their Probable Errors, for P_1 and S_1 were 6·189 ± 0·023 and 3·551 ± 0·007 km/sec.

The mean for all determinations, including that made with the aid of rockbursts, together with the Probable Error of the mean, proved to be: for P_1 6·234 ± 0·012 km/sec., and for S_1 3·544 ± 0·011 km/sec. Secondary arrivals, in general, satisfied the single-layer travel time curves developed for the rockburst profile, although in this case also there were variations from the curves such as might have been due to variations in rock type and variations in crustal thickness.

INTRODUCTION

Throughout the course of the rockburst travel-time studies described in the first paper of this series* it was occasionally possible to time large blasts at their source and to record them at one or more of the regular stations of the profile. It is the purpose of this, the second paper of the series, to present and analyse the data so obtained.

The blasts to be considered fall into two categories—those which were located in the line of the rockburst profile and those displaced from that line at some distance. Blasts of the former class provide additional information on velocities within the profile; in particular they allow the measurements of travel-times in the reverse direction. Blasts of the latter class permit an investigation of travel-time variations for paths lying wholly outside the rockburst profile.

In the present paper all notations introduced in the first paper of the series will be adhered to. In particular the station numbers of Table II and the quality indexes of Table III will be used throughout, while events will be numbered consecutively with those given in Table IV.

---

* Hodgson, J. H., "A Seismic Survey in the Canadian Shield, I: Refraction Studies Based on Rockbursts at Kirkland Lake, Ont.", *Publications of the Dominion Observatory*, Vol. XVI, No. 5, 1953.

FIELD TECHNIQUES

STATION-TIMED BLASTS AT ROLPHTON AND LA CAVE

Stations of the regular profile were maintained at Rolphton and La Cave (See Figure 9, Part I) for the purpose of recording rockbursts. This hope was never realized, but the stations did fulfil a useful purpose. Both locations were the sites of large hydro-electric power developments and blasts in connection with the work were automatically timed by the seismic stations. Frequently these were large enough to record at the other station of the pair and several records became available for analysis in this way. In a few instances the larger blasts were also recorded at Ottawa.

These blasts were recorded in the course of the routine operation of the stations when technical personnel were not available, so that no attempt was made to operate the recording drums at increased speed, nor to determine the precise location of the shot with respect the station. Distances are thus uncertain by about ± 1 km. and origin times by ± 0·2 sec. There was one exception to this. On February 12, 1950, a coffer dam at La Cave was blown by a large charge. Care was taken to time and locate this blast as precisely as possible.

PRECISELY TIMED BLASTS AT LA CAVE, TEMISKAMING AND SUDBURY

Location of Blasts

During the final summer of the field work, when Willmore-Sharpe seismometers were being used and two field stations were in operation, it became apparent that blasts were being recorded from various sources. After preliminary location by means of the seismic records three sources of these blasts were determined.

The first source was at La Cave, where large charges were being fired in connection with the power development. A second source, just south of Temiskaming, was also connected with this development for it was necessary to relocate a railroad which ran from La Cave to Temiskaming and this involved large rock cuts. Arrangements were made to time these blasts by a technique to be described later. The location of the shots was determined with relation to the development survey, and since this was tied in to a Geological Survey marker, precise location was possible. It is unfortunate that the heavy blasting was just about completed by the time machinery had been set up to time it, so that limited use was made of this source.

The remaining blast source proved to be the open-pit mines of the International Nickel Company near Sudbury (for location see Fig. 9, Part I). The officers of the Company very kindly permitted us to time the blasts and provided us with locations relative to a Geodetic Survey monument. The Sudbury blasts proved much more valuable to us than the La Cave series, producing quite usable records to distances of 173 km. despite the fact that the charges were in general, smaller. This is probably due to the fact that whereas at La Cave the blasts were close to the surface and in numerous holes fairly widely dispersed, the Sudbury blasts were designed to break up a limited section of a vertical face at considerable depth.

The geodetic coordinates of the Temiskaming, La Cave and Sudbury blasts were computed by officers of the Geodetic Service of Canada.

Timing Technique

The basic part of the equipment used in timing the blasts was a 6-channel, portable seismic recorder lent by the Ontario Department of Mines. This recorded the output of a geophone placed as close as possible to the blast, and, on a separate trace, the output of a chronometer which indicated every second second. The chronometer indicated the minute by omitting to mark the 60th second, and in practice the blast was set off as close as possible to the exact minute, so that the seconds on the record could be identified. Since the seismic recorder placed lines on the record at intervals of 0·01 sec. it was possible to time the first movement of the geophone relative to the second marks with an accuracy approaching 0·001 sec.

FIGURE 1—The blast timing equipment. It consisted of a six-channel seismic prospecting camera with storage batteries to supply power, a geophone and reel of cable of suitable length, a chronometer to indicate seconds and a control panel to adjust time mark amplitude.

In order to determine the error of the chronometer, time signals were recorded at half-hourly intervals for several hours before and after the blast, the signals being recorded on one galvanometer trace, the chronometer time on another. The chronometer could thus be precisely rated and its correction at the instant of the blast determined to within a few thousandths of a second.

When a blast was to be timed, the equipment was set up at the nearest source of power and radio signals recorded as described above. At the last possible moment the party would go to the site of the blast and set up the equipment at the point occupied by the shooter.

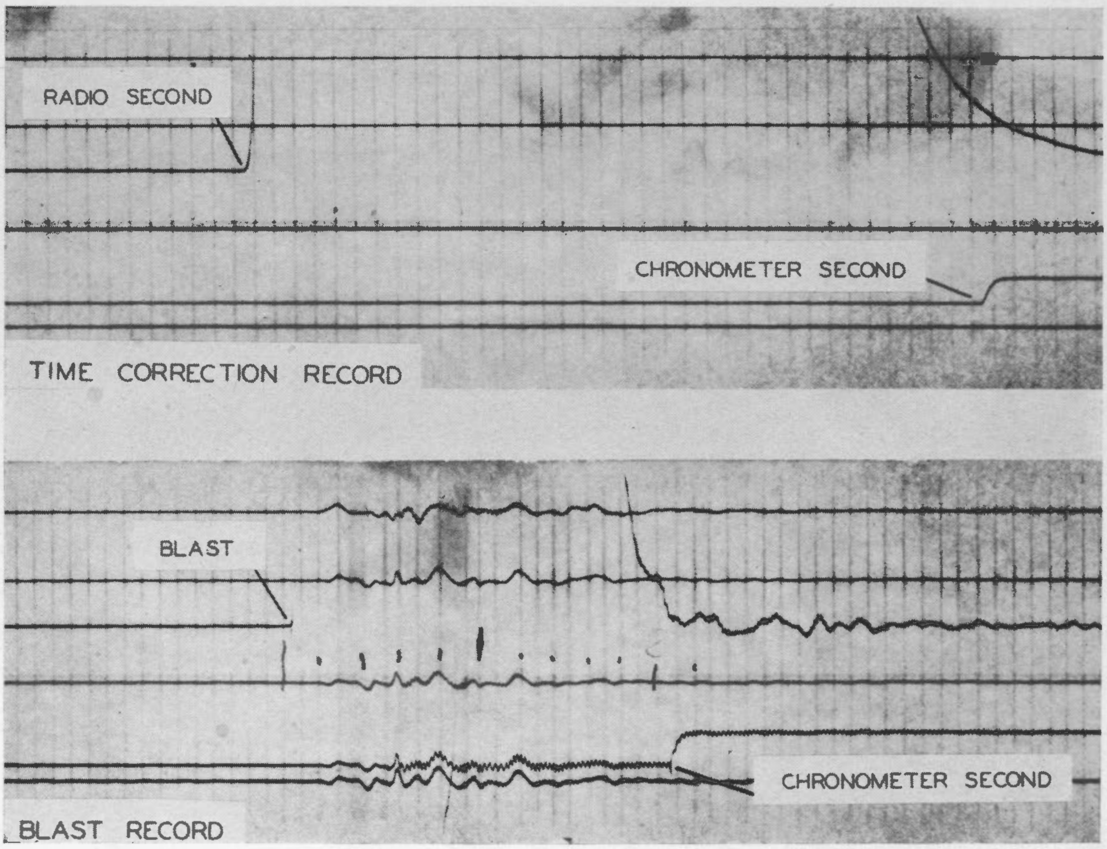


FIGURE 2—Time correction and blast records reproduced full scale. The time lines are at intervals of 0·01 sec.

In order that the identified second appear on the record the shooter would fire as nearly as possibly on the chronometer minute. Immediately after the blast the party would return to its base and continue to record time signals.

The radio signal was of sufficient amplitude that it could be recorded directly, without need of a relay. In Part I of this series it was argued that since relays were employed at the field station and at Kirkland Lake, only the difference in their reaction time contributed to the error of the observation. In timing the blasts this is no longer true, and an arbitrary time of 0·02 sec. has had to be allowed for the closing of the field station relays in computing the appropriate time correction.

PRESENTATION AND ANALYSIS OF DATA

STATION-TIMED BLASTS AT ROLPHTON AND LA CAVE

Presentation of Data

The precision of timing and location of this series of blasts was much inferior to that employed in other sections of this work. Moreover the record amplitude produced at distant stations was small and, in all cases, recording was at a conventional paper speed of 60 mm/min. It seems unnecessary to assign event numbers to each of the blasts; instead the recordings will be summarized in a single table. It will be noted that weights have been assigned to the blasts. These weights were based on record appearance—a weight of two being given to blasts which were particularly well recorded.

Discussion

The blasts recorded at mean epicentral distance of 83 km. (i.e. Rolphton to La Cave and La Cave to Rolphton) do not represent a serious interpretative problem. The first arrivals in the P and S groups must be P_1 and S_1 respectively. Mean travel-times obtained for these phases are $13 \cdot 2 \pm 0 \cdot 1$ sec. and $24 \cdot 1 \pm 0 \cdot 2$ sec. respectively, the uncertainties being Probable Errors of the means. Corresponding velocities are, for P_1 $6 \cdot 29 \pm 0 \cdot 04$ km/sec., and for S_1 $3 \cdot 44 \pm 0 \cdot 03$ km/sec., the uncertainties being those arising from the Probable Errors in the time measurements.

For the smaller blasts only the two phases were recorded, but in the case of the three blasts to which weight 2 has been assigned additional phases were present and there is some suggestion that these phases repeat themselves and so have physical validity. On the basis of the travel-time curves derived in Part I of this series one set has been assigned to S_n; in addition the P phase with travel-time of $19 \cdot 7$ sec. could be $P_1 P_1$ and the S phase with mean travel-time of $24 \cdot 7$ could be $P_1 S_1$. Such assignment is of course very arbitrary. The remaining phases are unaccounted for by the travel-time curves. However they follow S_1 so closely that they may well represent S_1 phases travelling by longer paths provided by lateral variations in rock type.

While the Rolphton blasts produced at Ottawa records of great simplicity, it is difficult to identify the phases with certainty. This is because the distance of 177 km. is close to critical for both P and S phases. The records begin with a single P phase of small amplitude (the arrival times are listed as P_n in Table I). If this is interpreted as P_1 it shows a P_1 velocity of $6 \cdot 25 \pm 0 \cdot 05$ km/sec., a very reasonable value. However, on the basis of the rockburst work we would expect P_1 to be small at this distance and P_n fairly large. Since there is only one phase present it has been assigned to P_n, but it should be pointed out that it arrives about 1 second early. The interpretation is certainly open to question.

In the S group we are faced with a similar problem. Here there are two phases, a small initial phase followed after an interval of about $0 \cdot 7$ seconds by a larger phase. The rockburst travel-time curves suggest that these are S_1, S_n respectively but the large phase

TABLE I.—*Summary of Station-Timed Blasts*

Date	H time E.S.T.	Wt.	TRAVEL-TIMES (seconds)										
			P_n	P_1			S_n	S_1	Rg				
Mean Epicentral Distance 83 km.													
Rolphton Blasts recorded at La Cave													
11–23–49	18:15:23·7	1		13·3				23·6					
11–24–49	06:16:10·3	1		14·0				25·6					
11–24–49	12:10:27·6	2		13·4			30·3	24·3			26·3		29·1
11–28–49	12:38:00·7	1		12·5				23·1					
1–26–50	18:09:13·7	1		12·8				24·3					
3–22–50	06:18:50·6	2		12·9			31·1	24·3		24·6	25·8	28·0	28·3
La Cave Blast recorded at Rolphton													
2–12–50	10:01:36·5	2		13·5	19·7		29·7	23·6		24·8	26·5	27·6	28·7
Mean for Δ = 83				13·2 ± 0·1	19·7		30·4	24·1 ± 0·2		24·7	26·2	27·8	28·7
Mean Epicentral Distance 177 km.													
Rolphton Blasts recorded at Ottawa													
11–24–49	12:10:27·6	1	28·9				51·1	51·8					
11–28–49	12:38:00·7	1	27·7			30·1	50·6	51·2					
12– 5–49	12:24:05·4	1	27·4				49·7	50·3					
12– 8–49	18:01:23·9	1	27·9				50·4	51·0					
12– 8–49	18:24:36·8	1	27·7				49·9	50·6					
12–14–49	18:11:28·8	1	28·7				50·9	51·7	59·4				
12–14–49	18:13:16·5	1						52·0					
1–14–50	12:33:18·5	1	28·9					51·9					
1–14–50	17:26:43·6	1					50·7	51·3					
1–26–50	18:09:13·7	1	28·9					51·4	58·9				
Mean for Δ = 177			28·3 ± 0·2			30·1	50·5 ± 0·1	51·3 ± 0·1	59·2				
Epicentral Distance = 258 km.													
La Cave Blast recorded at Ottawa													
2–12–50	10:01:36·5		40·0				68·3	73·3					

looks so much like the prominent S phase in the distant-station rockburst records that this designation has been reversed in the table. Again this interpretation is arbitrary. Those entries given under S_n would, if treated as S_1 give a velocity of $3 \cdot 50 \pm 0 \cdot 01$ km/sec., while the phases listed under S_1, give the velocity of $3 \cdot 45 \pm 0 \cdot 01$ km/sec. At least one can conclude that no second layer is necessary to account for the number of phases observed.

A well-defined surface wave, presumably of the Rayleigh type since is recorded on the vertical component, is apparent on some of the records.

The record produced at Ottawa by the La Cave blast was of extremely small amplitude, and shows only three phases designated P_n, S_n, and S_1. In this case S_1 is a distinct phase but of small amplitude.

The only conclusion which may safely be drawn from the station-timed blasts is that the records do not demand a more complicated crustal structure than that already postulated, and that the indicated velocities lie within the range of those already determined, when the uncertainties of timing and location are considered.

PRECISELY TIMED BLASTS AT LA CAVE, TEMISKAMING AND SUDBURY

Table II lists the pertinent information for the two series of blasts to be discussed in this section. The station numbers used are those given in Table II of Part 1 of this series, and the quality of the observations have been evaluated according to the code outlined in Table III of that paper. Event numbers have been continued consecutively from those in the earlier Table IV.

TABLE II.—*Data on Precisely Timed Blasts*

Event No.	Location of Blast	Date	Time E.S.T.	Azimuth, Blast to Station	Recorded at Station No.	Quality of Observation	Paper Speed	Δ km.	Elevation of Blast, feet
60	Temiskaming	6:22:50	13:18:01·27	N 24° 17′ W	9	a a a	150	107·01	+ 670
61				N 24° 40′ W	8	a a a	150	118·00	+ 670
62	La Cave	6:13:50	17:15:01·33	N 27° 49′ W	9	a a a	112	143·63	+ 480
63				N 27° 35′ W	8	a a a	112	154·60	+ 480
64	La Cave	6:27:50	17:12:00·38	N 30° 07′ W	6	a a c	150	178·57	+ 480
65				N 29° 09′ W	4	a a c	150	197·10	+ 480
66	Sudbury	8:1:50	15:54:01·05	N 73° 52′ E	14	a a a	150	139·18	+ 725
67				N 68° 06′ E	13	a a a	150	140·80	+ 725
68	Sudbury	8:2:50	Untimed	N 73° 31′ E	14	a d a	150	140·97	+ 680
69				N 67° 50′ E	13	a d a	150	142·67	+ 680
70	Sudbury	7:13:50	11:15:02·77	N 60° 14′ E	12	a a a	150	145·47	+ 680
71				N 52° 24′ E	10	a d a	150	149·29	+ 680
72	Sudbury	7:14:50	15:56:01·20	N 52° 18′ E	10	a a a	150	149·90	+ 796
73	Sudbury	6:20:50	11:16:02·83	N 43° 54′ E	9	a a a	150	152·93	+ 916
74				N 40° 08′ E	8	a a a	150	157·18	+ 916
75	Sudbury	6:28:50	11:19:02·74	N 31° 10′ E	6	a a a	150	160·96	+ 680
76				N 26° 14′ E	4	a a a	150	173·28	+ 680
77	Sudbury	6:29:50	11:08:01·38	N 26° 02′ E	4	a a a	150	171·46	+ 706
78				N 31° 00′ E	6	a a a	150	159·07	+ 706

The data will be discussed in two sections, the first consisting of blasts at La Cave and Temiskaming which constitute a reverse profile, the second of the blasts from Sudbury.

Reverse Profile Blasts

Presentation of Data.—Travel times of phases to be discussed in this section have been given in Table III.

TABLE III.—*Reversed Profile Travel-Times*

Event No.	Δ km.	Travel-Times and Residuals (seconds)								
		P_1		P_2		S_1		S_2		
		Travel Time	Residuals Eqn. 1	Travel Time	Residuals Eqn. 3	Travel Time	Residuals Eqn. 2	Travel Time	Residuals Eqn. 4	Residuals Eqn. 5
60	107·01	17·10	− ·20	19·34	− ·01	29·79	− ·50	33·50	+ ·24	− ·53
61	118·00	19·11	+ ·03	20·78	− ·12	33·53	+ ·13	35·97	− ·09	− ·60
62	143·63	—	—	24·59	+ ·08	40·85	+ ·20	42·37	− ·23	− ·25
63	154·60	25·17	+ ·18	26·12	+ ·06	43·82	+ ·06	45·25	− ·14	+ ·04
64	178·57	28·81	− ·06	29·58	+ ·14	—	—	51·73	+ ·23	+ ·86
65	197·10	—	—	31·88	− ·17	—	—	—	—	—

The travel-times have been reduced to a sea-level datum and have been corrected for the delay in the relay closing as mentioned in an earlier section.

It will be noted that entries have been made for phases designated P_2 and S_2. These were very prominent phases, P_2 lying between P_1 and P_n, and S_2 between S_1 and S_n. Because of their prominence they raised once again the possibility of the existence of a second layer. These phases were particularly prominent in the records of the Temiskaming blast but could be observed at all the distances given in Table III. Except at the shorter distances these prominent phases obscured the section of the record in which P_n and S_n might be expected, so that no independent reading of those latter phases has been possible.

The Direct Phases, P_1 and S_1.—As the table suggests, neither of these phases was prominent. In the case of P_1 this corroborates the observation made in the rockburst profile that P_1 is seriously attenuated with distance. The reduced magnitude of S_1 is perhaps to be expected in view of the fact that blasts provided the energy source.

Data listed under P_1 and S_1 were fitted to straight lines by method of least squares. The resulting equations were:

for P_1
$$t = 0\cdot29 \pm 0\cdot25 + \frac{\Delta}{6\cdot12 \pm 0\cdot07},$$

and for S_1
$$t = -1\cdot29 \pm 0\cdot55 + \frac{\Delta}{3\cdot416 \pm 0\cdot049}.$$

As in previous dealings with these surface phases the constant term was dropped and the line required to go through the origin. In this case the equations became

for P_1
$$t = \frac{\Delta}{6\cdot19 \pm 0\cdot07}, \qquad (1)$$

and for S_1
$$t = \frac{\Delta}{3\cdot535 \pm 0\cdot072}. \qquad (2)$$

Residuals from these two equations are listed in Table III. The probable errors in the velocities are considerably larger than those obtained in the rockburst profile. This may arise from a tendency to read the phases late, for in most cases the amplitude is small, but in addition the relatively small number of observations must lead to an increased probable error.

The Phases P_2, S_2.—As was mentioned earlier, these phases were so prominent as to force a reconsideration of the possible existence of a second layer. The best straight line fit to the two sets of data are the following:

$$\text{for P} \qquad t = 4{\cdot}26 \pm 0{\cdot}16 + \frac{\Delta}{7{\cdot}093 \pm 0{\cdot}052}, \tag{3}$$

$$\text{and for S} \qquad t = 5{\cdot}98 \pm 0{\cdot}15 + \frac{\Delta}{3{\cdot}923 \pm 0{\cdot}017}. \tag{4}$$

Combining the first of these equations with those for P_1 and P_n in the rockburst profile one can solve for the dimensions of the corresponding two-layer crust. The thickness of the first layer works out to be 28·1 km., that of the second 12·1 km., a total thickness of 40·2 km. Using the S travel time curves the equivalent thicknesses prove to be 24·6 and 24·6 km. for a total of 49·2 km.

This discrepancy might have been interpreted immediately as a failure of the hypothesis, but, considering the large probable error in the equation for S_n and the consequent errors in crustal dimensions, a further investigation seemed desirable. The crustal dimensions determined from the P waves were adopted as standard and travel-time curves for all secondary phases to be expected in a two-layer crust were computed. In order that the S and P values should be consistent it was necessary to adjust the equations of S_2 and S_n to give the same crustal dimensions as the P waves. This was done by successive trial and error computations, the constant term being selected and the best least-square determination of the slope determined. The equation finally adopted for S_2 was the following:

$$t = 8{\cdot}68 + \frac{\Delta}{4{\cdot}234}, \tag{5}$$

which differs considerably from that originally determined. Residuals from this equation are shown in Table III.

When the travel-time curves for the hypothetical two-layer crust had been plotted, observed arrivals were compared with the curves. Except for the phases listed in Table III there was no confirmation of the curves whatever; moreover the numbers of phases observed did not appear to justify the hypothesis, which was therefore discarded.

A second hypothesis was next considered. Could the phases under consideration be P_n and S_n, their travel-time curves displaced due to dip? Combining equation (3) with equation (3) of Part I for P_n it is possible to determine dip and true velocity. The results of this computation were as follows:

Angle of dip = 4°48′
True P_n velocity = 7·453 km/sec.
Thickness of crust under Kirkland Lake = 39·5 km.
Thickness of crust under La Cave = 24·4 km.

Using the S waves we obtain:

Angle of dip = 8°50′
True S_n velocity = 4·29 km/sec.
Thickness of crust under Kirkland Lake = 51·9 km/sec.
Thickness of crust under La Cave = 19·1 km/sec.

The inconsistencies between the P and S determinations are not sufficient to allow one to discard the hypothesis, for in the S determination a value of S_n has been used based entirely on the distant stations. The most telling argument against the hypothesis is the low velocities it yields for P_n and S_n. In addition the conclusion that the crust is more shallow under La Cave than under Kirkland Lake is in contradiction to the observation of gravity[1] for these measurements suggest a thickened crust under La Cave.

Thus neither of the hypotheses so far considered are adequate to account for the phases. One final possibility should be raised. Is it possible that the phase interpreted as P_n in Part I of this series is in fact a phase P_2, constrained by the fortuitous arrangement of dip to give a travel-time equation very similar to the expected equation of P_n? It seems most improbable, but without filling up the blank in the rockburst profile between Temiskaming and Ottawa, no argument based on first arrivals can be advanced. It should be mentioned, however, that such uniformity of dip as is implied by the small residuals in the rockburst P_n equation and the reverse profile P_2 equation seems unlikely to be obtained in a Precambrian area. It should also be realized that the travel-time curves for secondary phases in the presence of such a dipping bed would be much modified. While the fit obtained in the rockburst records was not very close, at least the curves based on a uniform crust did account quantitatively for the observations.

At this stage then it is necessary to conclude that the phases called P_2 and S_2 cannot be interpreted in terms of a second layer. As in Part I of this series, we must assign these arrivals to phases which have travelled a minimum path other than the direct one, provided by lateral variations in rock type.

Sudbury Blasts

Examination of Table II will show that the Sudbury blasts were not recorded over a sufficient range of distance to allow the construction of a satisfactory refraction profile. Their principal interest lies, on the contrary, in the variation of azimuth through which they were recorded. The several traverses involve widely differing sections of the Huronian basin. This large basin consists principally of metamorphosed sedimentary rocks of various types. Its thickness at its southern boundary has been estimated[2] at about 23,000 feet, say 7 km. roughly, and it presumably thins towards the north although no estimate of the rate of thinning appears to have been made. When the opportunity arose to time the Sudbury blasts it seemed to offer a desirable chance to study the variations to to be expected in P_1 and S_1 velocities.

---

[1] Garland, G. D. "Interpretations of Gravimetric and Magnetic Anomalies on Traverses in the Canadian Shield in Northern Ontario", *Publications of the Dominion Observatory*, Vol. XVI No. 1, 1950.

[2] Quirke, T. T., and Collins, W. H. "The Disappearance of the Huronian", Geological Survey of Canada, Memoir 160.

Travel-Times for P_1 and S_1.—Travel-times for P_1 and S_1 are given in Table IV. The readings have been corrected for the delay in relay closing. P_1 exhibits the amplitude characteristics which we have observed earlier, being of very small amplitude throughout. S_1 is not a well defined phase and some recourse has had to be had to the expected arrival times in identifying it. In this sense the S_1 observations are not as unbiased as might be desired.

TABLE IV.—*Sudbury Blasts, Travel-Times and Velocities*

Event No.	Δ km	TRAVEL-TIMES (seconds)		VELOCITIES AND RESIDUALS (km. per second)			
		P_1	S_1	P_1		S_1	
				Velocity	Residual	Velocity	Residual
66	139·18	23·00	39·70	6·051	−0·138	3·506	−0·045
67	140·80	22·95	—	6·135	−0·054	—	—
70	145·47	23·77	—	6·120	−0·069	—	—
72	149·90	24·47	42·44	6·126	−0·063	3·532	−0·019
73	152·93	25·22	43·19	6·064	−0·125	3·541	−0·010
74	157·18	25·39	44·55	6·191	+0·002	3·528	−0·023
75	160·96	25·73	45·19	6·256	+0·067	3·562	+0·011
78	159·07	25·47	44·65	6·245	+0·056	3·563	+0·012
76	173·28	27·26	48·06	6·357	+0·168	3·605	+0·054
77	171·46	27·01	48·01	6·348	+0·159	3·571	+0·020

Considering the variations in azimuth, and the poor distance distribution of stations, it seems undesirable to fit the observations to straight line curves. Instead the velocities have been computed in each separate observation simply by dividing epicentral distance by observed time. The mean velocity obtained for P_1 is $6 \cdot 189 \pm 0 \cdot 023$ km/sec. the uncertainty being the Probable Error of the mean. The equivalent S_1 value is $3 \cdot 551 \pm 0 \cdot 007$. The low Probable Error of this latter mean suggests that the selection of S_1 has not been completely objective, although every effort was made to make it so.

If the P_1 data given in Table IV are treated as defining a refraction profile and fitted to a straight line equation it works out to be

$$t = 5 \cdot 42 \pm 0 \cdot 57 + \frac{\Delta}{7 \cdot 906 \pm 0 \cdot 023} .$$

Since the velocity indicated is a P_n velocity it was tempting to speculate on the possibility that the crust under Sudbury was much thinner than that under the principal rockburst profile. However, as we shall see in a later section, P_n and S_n, as well as P and S phases reflected from the base of the crust seem to have been well recorded at all distances approximately as forecast by the rockburst travel-time curves. Apparently the P_n velocity obtained by routine least-square analysis of the first arrivals is a matter of accident, resulting principally from the grouping of stations over a short distance range, the group being at considerable distance from the blast source. It might be mentioned that several other interesting possible interpretations of the Sudbury blast data have been discarded on the grounds that the traverse is not appropriate for such analysis.

Secondary Arrivals:—Secondary arrivals on the Sudbury blast records have in general given a very satisfactory fit to the single-layer travel-time curves obtained in the rockburst profile. As in the rockburst profile the fit has not been exact, and sometimes a burst of energy occurs instead of a single sharp phase, but in a general way the curves do appear to account for the principal phases observed. P_n, S_n, P_1P_1, and S_1S_1 are apparently observed over the range of the observations and a phase fitting the curve for S_1P_1 has been observed at some stations.

Recalling the fact that the reverse-profile blasts suggested the existence of a phase P_2, it should be mentioned that a number of strong phases lying intermediate between P_1 and P_n may be fitted to the following equation:

$$t = 3{\cdot}81 \pm 0{\cdot}86 + \frac{\Delta}{7{\cdot}03 \pm 0{\cdot}27}\,.$$

Again it should be stressed that the analysis of the data by profile technique is of questionable merit. At first it was thought that this phase might be one refracted beneath the Huronian basin. However, the thickness of the basin so determined works out to be 22 km., a most unreasonable figure, so that the hypothesis has had to be discarded. Again we must assume that the phases in question are due to propagation over other minimum paths than the direct one.

Under the circumstances we shall be content to note that the Sudbury blasts appear in general to confirm the single layer hypothesis and provide us with some idea of the variations to be expected in surface velocities.

DISCUSSION

Data obtained from the various blasts have been summarized in Table V which provides also a comparison with the results obtained in the rockburst profile. Weighted means of the P_1 and S_1 velocity determinations are included in the table, the several measurements having been weighted inversely as the squares of their probable errors. It is unfortunate that more observations cannot be included on P_n and S_n, but in the case of the station timed blasts and the Sudbury blasts, in each of which P_n and S_n were observed, the traverse was not adequate for profile analysis, while in the case of the reverse profile blasts P_n and S_n were obscured by the phases P_2 and S_2.

TABLE V.—*Summary of Velocity Determinations*

Source	Velocities and Probable Errors (km. per second)					
	P_1	P_2	P_n	S_1	S_2	S_n
Rockburst Profile	6·246 ± 0·015		8·176 ± 0·013	3·544 ± 0·023		4·85 ± 0·10
Reverse Profile Blasts	6·19 ± 0·07	7·093 ± 0·052		3·54 ± 0·07	3·923 ± 0·017	
Sudbury Blasts	6·189 ± 0·023	7·03 ± 0·27		3·551 ± 0·007		
Station Timed Blasts	6·29 ± 0·04			3·44 ± 0·03		
Weighted Means	6·234 ± 0·012			3·544 ± 0·011		

Velocities for the phases P_2 and S_2 have been included in the table, in order that their existence shall not be forgotten, but it should be recalled that the existence of a two-layer crust could not be established.

The results from the blast records are interesting in several ways. First of all they establish that results from blasts provide satisfactory data on both P and S waves. It was the realization of this fact that led to the decision not to continue observations on the rockburst profile until it had been completed in the final details. Instead the program is being reinstrumented and will be carried on primarily with blasts.

What lessons can we learn from the present work as a guide to the future? First of all, because of the doubt that must still exist in connection with the extra phases (P_2, S_2) observed on the reverse profile blasts, we must still be alert for evidence of a second layer. Secondly, since reflections seem to have been well-recorded close to the critical angle, and since the thickness of the crust is variable, we should endeavour to make more efficient use of these reflections. An enlarged program based on blasts should allow for the correlation of reflections from point to point, and techniques of ordinary reflection seismology should be adopted as much as possible. Thirdly we should endeavour to work in as many different areas as possible, since the area here investigated has been a relatively small one. Finally it seems probable that seismic methods might be used with advantage in problems involving finer structure—such for example as the structure of the Huronian basin—and this suggests that more open time-scales should be employed than have been utilized in the present work.

CONCLUSIONS

The conclusions of the present paper are largely provided in Table V. In addition it should be noted that, while the single-layer is not quite as well established as it appeared to be from the rockburst work, still there are no serious objections to accepting it as a working hypothesis. As in Part I, if we accept the hypothesis that the crust is heterogenous because of various rock-types involved, and of the variable thickness suggested by gravity observations, it seems possible to account in general for the phases observed.

ACKNOWLEDGMENTS

In addition to the acknowledgments at the end of Part I, which apply equally here, it is a pleasure to acknowledge our indebtedness to the Hydro Electric Power Commission of Ontario, for assistance in timing and locating blasts at La Cave and Rolphton, and to the International Nickel Company of Canada for help in connection with those at Sudbury. The work at Sudbury was carried out with the very kind permission of Mr. R. D. Parker, Assistant Vice-President and General Superintendent of the Mining and Smelting Division, and Mr. P. I. Ogilvie made the detailed arrangements and assisted most ably in the timing of the blasts. At La Cave we were particularly indebted to Mr. W. B. Crombie, Project Manager, and to Mr. H. A. Jackson, Major H. J. MacCrimmon and Mr. P. E. Brulé.

PLATE I *upper*

THE COBEQUID FAULT—This fault marks the boundary between the flat-topped Cobequid uplands in the back- ground and the Triassic and Carboniferous lowlands in the middle distance. It produces a marked effect on the gravity anomaly field.

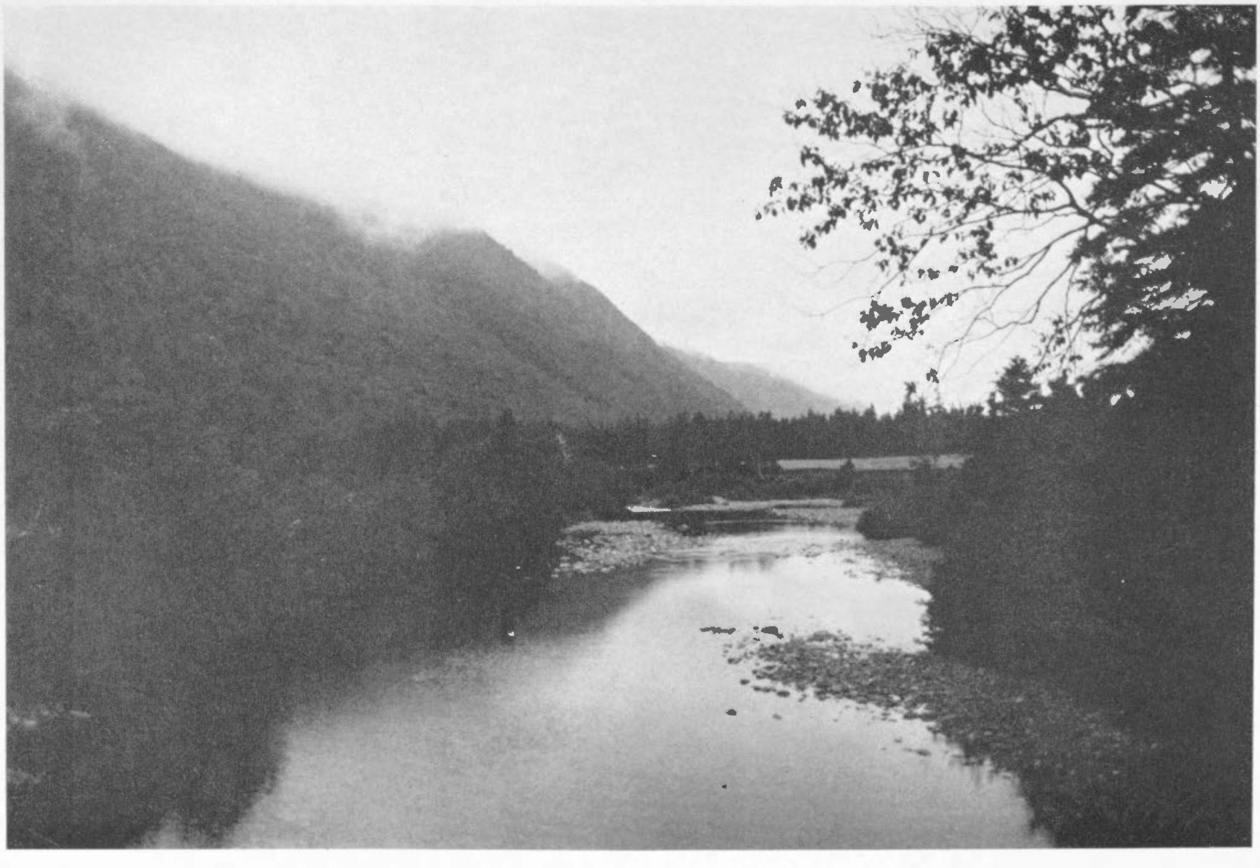


PLATE I *lower*

CAPE BRETON ISLAND TOPOGRAPHY—The highlands are formed of dense, pre-Carboniferous rocks, while the lowlands are underlain by Carboniferous formations. In general there are strong gravity gradients at the borders of the highland.

CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
DOMINION OBSERVATORIES

PUBLICATIONS

OF THE

Dominion Observatory

OTTAWA

VOL. XVI No. 7

GRAVITY MEASUREMENTS IN THE MARITIME PROVINCES

BY

G. D. GARLAND

EDMOND CLOUTIER, C.M.G., O.A., D.S.P.
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
OTTAWA, 1953

CONTENTS

ILLUSTRATIONS

TABLES

GRAVITY MEASUREMENTS IN THE MARITIME PROVINCES

BY G. D. GARLAND

ABSTRACT: The results of all regional gravity measurements made by the Dominion Observatory in Nova Scotia, New Brunswick and Prince Edward Island are given, and the correlation of the Bouguer anomalies with major geological structures is discussed. It is shown that most of the anomalies may be related to the densities of known formations. In several cases, the depth extents of these formations are estimated from their gravitational effects. A rather detailed interpretation is made of the structure of the Carboniferous basin in the region of Moncton, New Brunswick.*

INTRODUCTION

The purpose of this report is first, to present in tabular form the results of all gravimeter observations made to date in the Maritime Provinces (Nova Scotia, New Brunswick and Prince Edward Island), and secondly to offer an interpretation of the major features of the gravity anomaly field over the area. Gravity observations in these provinces date from the pendulum measurement made by Putnam (17) of the United States Coast and Geodetic Survey at Sydney, Nova Scotia, in 1896. Observations with gravimeters, however, were not begun until 1944. Since that year, parties of the Dominion Observatory have spent several seasons in the area, and a large amount of data has been accumulated. A variety of instruments were used, and different base values were adopted through the years, so that the adjustment of all observations to a uniform datum was a considerable problem. The mechanics of the adjustment are discussed, and the main bases, to which all other stations have been connected, are described. Tables of principal facts for gravity stations are given in the Appendix for each of the three provinces, with the stations arranged in order of increasing latitude.

Bouguer anomalies have been employed exclusively for the geological interpretation of the results. As most of the area is covered with stations spaced about eight miles or more apart, only the broad, regional gravity trends can be outlined with certainty. In some regions of particularly difficult access, the tracing of even these large scale features is uncertain. However, in southeastern New Brunswick, a comparatively dense network of stations has been established and a special chapter is devoted to the analysis of more local gravity anomalies in this section of the province.

THE GRAVITY OBSERVATIONS AND THEIR ADJUSTMENT

The results of gravity measurements in New Brunswick and Nova Scotia in 1944 have already been described by Miller (14). These observations were made with a Humble Truman-type gravimeter, which was also employed during the season of 1945. In 1947, an Atlas gravimeter was used by Miller for the establishment of several hundred stations in New Brunswick, and for repeating the base stations of the previous years. The observations of 1950 were made during three trips into the area, one conducted by M. J. S. Innes and two by the writer. A North American instrument was used throughout that season, although a few stations were observed with a Worden gravimeter also.

---

* The principal results of the interpretation were presented at the 1951 meeting of the American Geophysical Union in Washington.

The adjustment of the values of observed gravity may be broken down into three stages: the adoption of a value of gravity at some fundamental base for the entire region, the interconnections of numerous subsidiary bases to this point and to one another, and the connection of all other stations to these bases. For the fundamental base, the pendulum station at Amherst (12) has been chosen, partly because of its central location and partly because the original pendulum value of 980·693 gals. appears to be free from serious error. As the result of four independent connections between Amherst and points closer to Ottawa, a value of 980·6929 cm. per sec. per sec. was obtained for the former station, relative to the value 980·6220 for Ottawa. It would appear, therefore, that for the present one could not do better than to adopt the value of 980·6930 for Amherst, and this has been done in the adjustments which follow.

The strength of the connections of the other bases to Amherst is variable over the area and a rigorous overall adjustment does not seem possible. In southern New Brunswick and the mainland of Nova Scotia the values of practically all of the bases were obtained either as a result of detailed looping, or by numerous single connections of short time duration. As the instruments used in 1947 and 1950 had very low drift rates, the values should be good to within a few tenths of a milligal. The bases in Prince Edward Island were also interconnected by either closed loops or short, repeated legs, and tied directly to Amherst before and after the ferry crossings. However, on Cape Breton Island and in northern New Brunswick the adopted base values were in general obtained by repeated single connections of several hours duration, or by day-long "loops". These values will therefore be less reliable than those of bases closer to Amherst. The results of repeat observations suggest that the values of observed gravity of all of the bases, relative to Amherst, are correct to within about one-half milligal.

In order to facilitate the re-location of base stations at a later date, sketches are given, indicating the station positions relative to easily identified features. Most of the bases were chosen near railway stations or public buildings, to insure a degree of permanence to the sites. The sketches should permit the positions to be recovered to within ten feet of horizontal position and one foot of elevation.

The third factor in the adjustments, that of referring all station values to one or another base, presented no problem except in the case of some of the 1944 and 1945 observations. During these years a number of long, cross-country traverses were made. In some cases, only the end points of these traverses have been repeated or established as bases, and very often a discrepancy of a milligal or more was found between the adjustments at the two ends of a single traverse. This is hardly surprising, considering the relatively high drift rate of the instrument used for the earlier work, and the rough country over which the traverses were carried. In these cases, the discrepancy between the end points was distributed uniformly among the intermediate stations. The largest adjustment of this type was required by the traverse of 1944 around northern Nova Scotia, where a misclosure of four milligals was found. It is interesting to note that Miller (14) predicted an error of this magnitude at the time, by observing the behaviour of the instrument after travelling over exceptionally rough roads. Practically all of the observations of 1947 and 1950 were made on loops or short traverses between bases, so that the intermediate station values are nearly as reliable as the base values for the district.

BASES IN NOVA SCOTIA

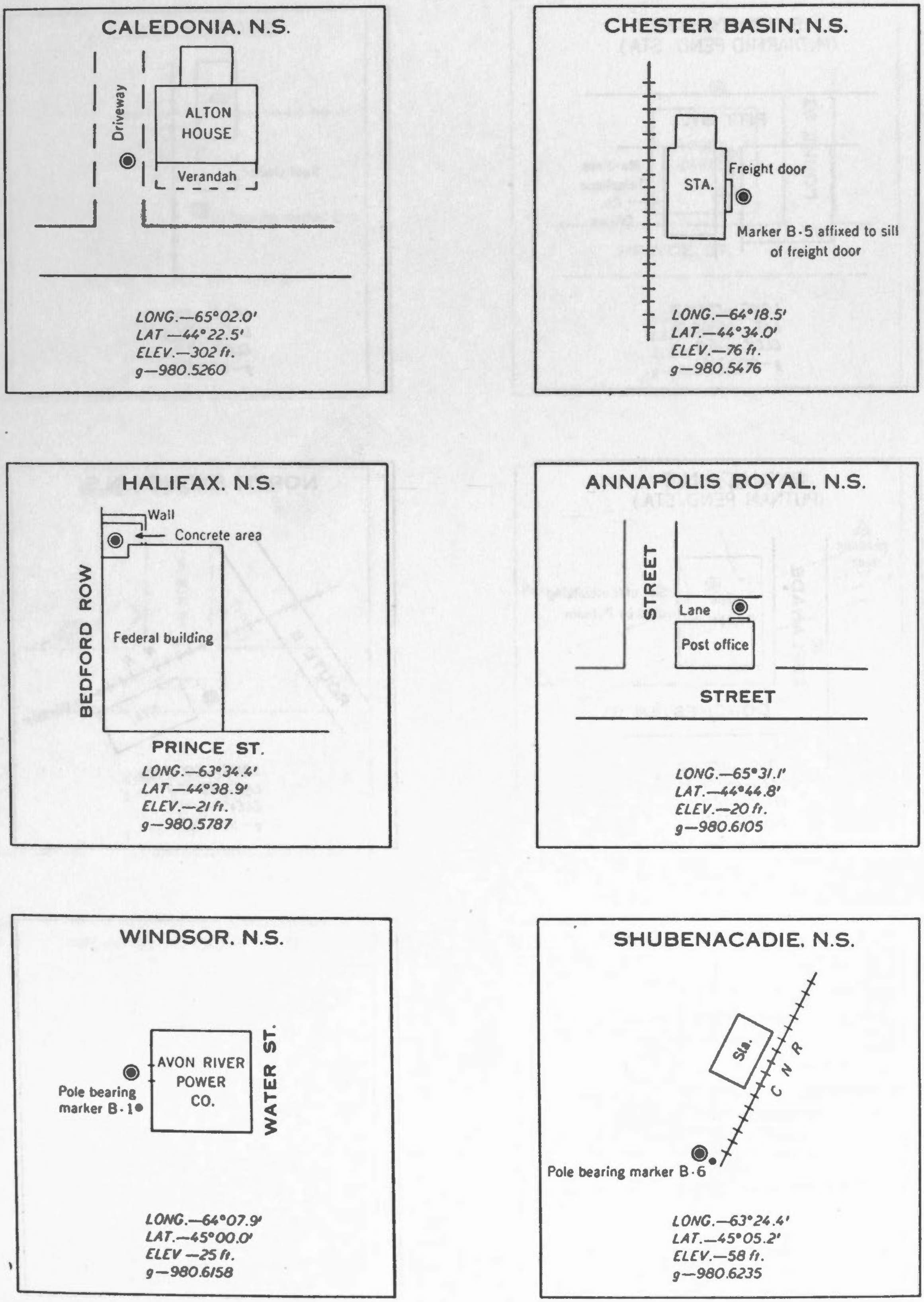


FIG. 1 (a). Location of gravity bases in Nova Scotia. In this and the following sketches, north is at the top of the page, and the scale is approximately 1 inch to 100 feet.

BASES IN NOVA SCOTIA

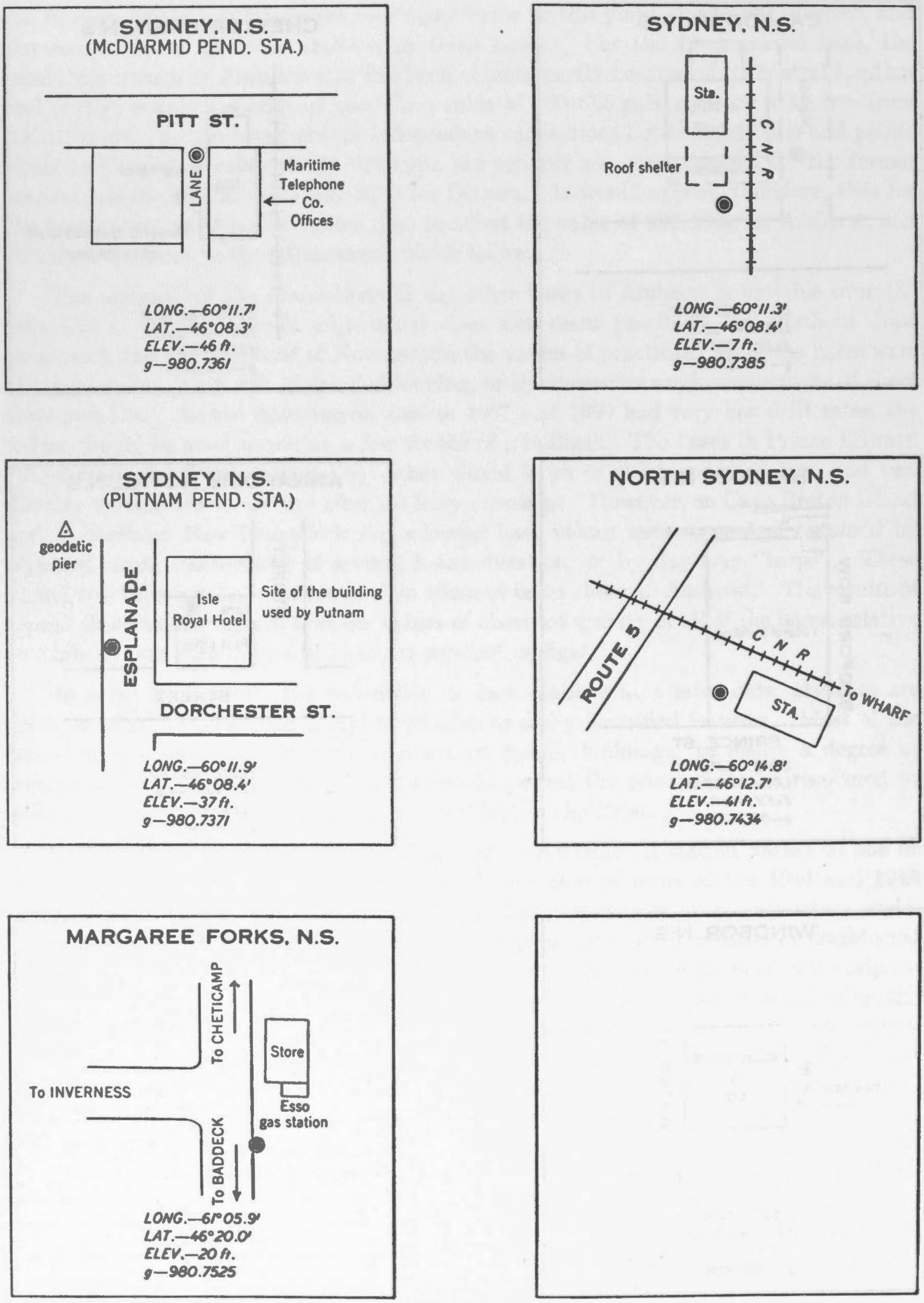
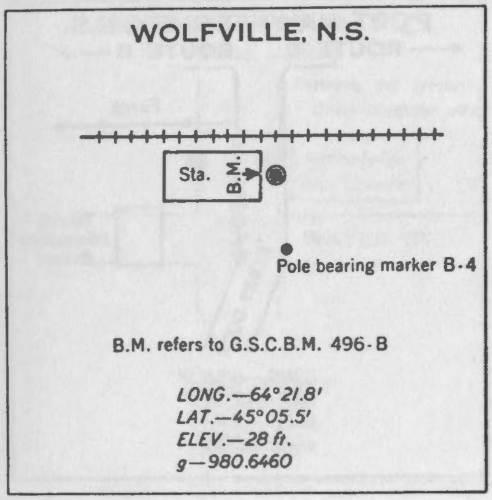


FIG. 1 (*b*). Location of gravity bases in Nova Scotia.

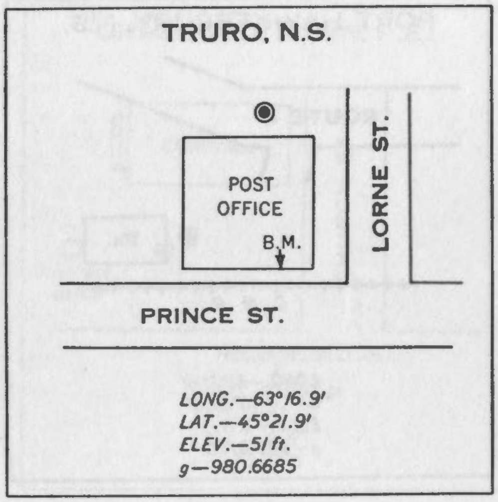
BASES IN NOVA SCOTIA



WOLFVILLE, N.S.

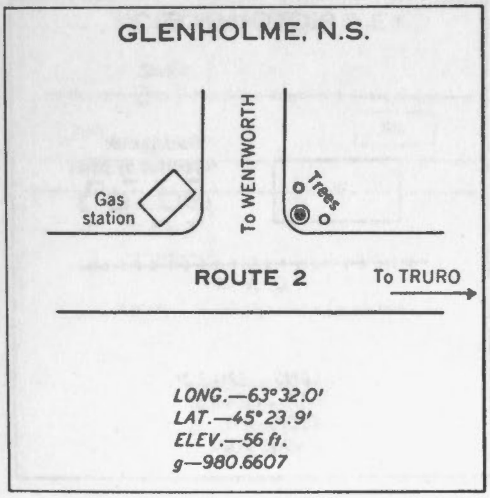
B.M. refers to G.S.C.B.M. 496-B

LONG.—64°21.8′
LAT.—45°05.5′
ELEV.—28 ft.
g—980.6460



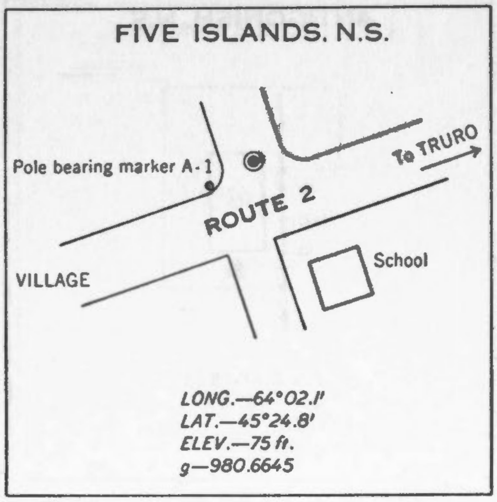
TRURO, N.S.

LONG.—63°16.9′
LAT.—45°21.9′
ELEV.—51 ft.
g—980.6685



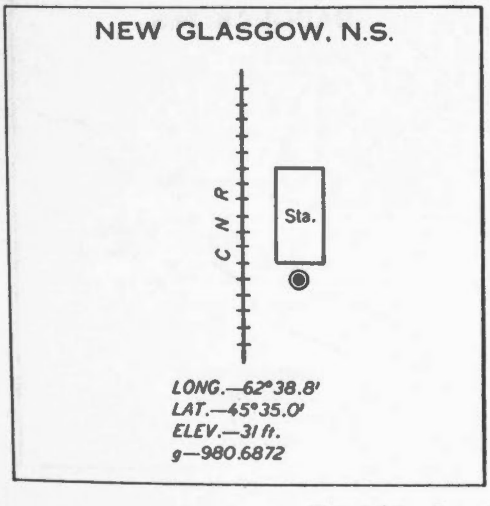
GLENHOLME, N.S.

LONG.—63°32.0′
LAT.—45°23.9′
ELEV.—56 ft.
g—980.6607



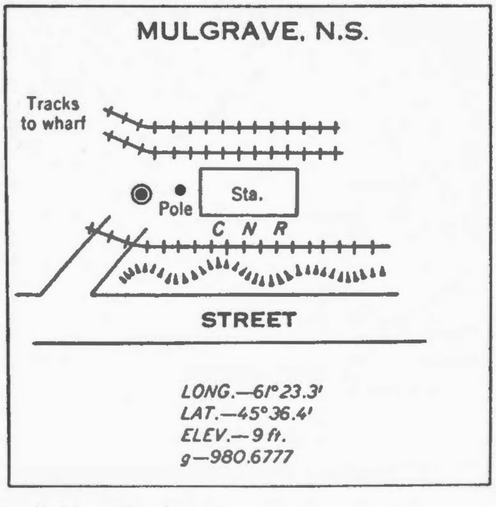
FIVE ISLANDS, N.S.

LONG.—64°02.1′
LAT.—45°24.8′
ELEV.—75 ft.
g—980.6645



NEW GLASGOW, N.S.

LONG.—62°38.8′
LAT.—45°35.0′
ELEV.—31 ft.
g—980.6872



MULGRAVE, N.S.

LONG.—61°23.3′
LAT.—45°36.4′
ELEV.—9 ft.
g—980.6777

FIG. 1 (*c*). Location of gravity bases in Nova Scotia.

BASES IN NOVA SCOTIA

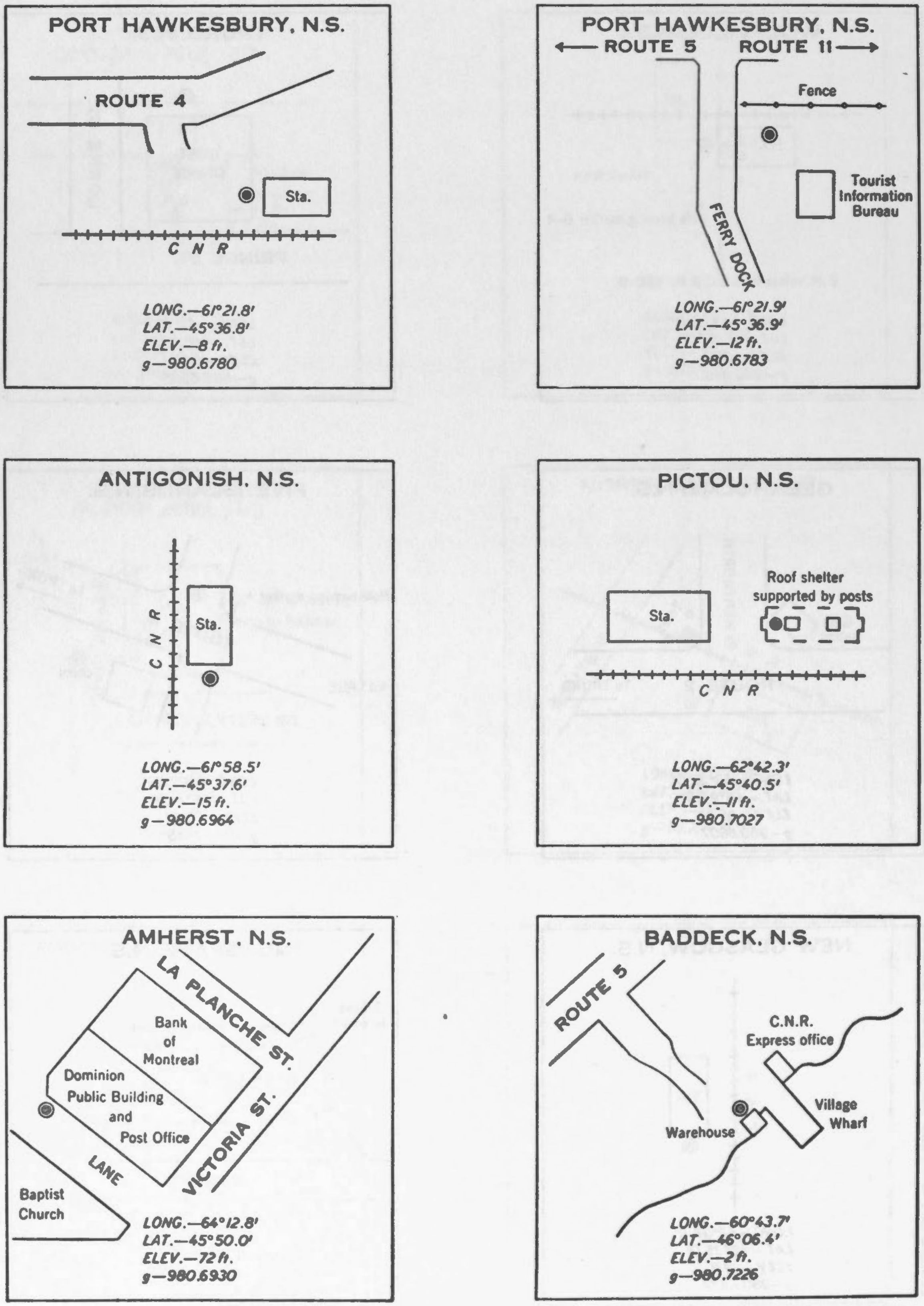
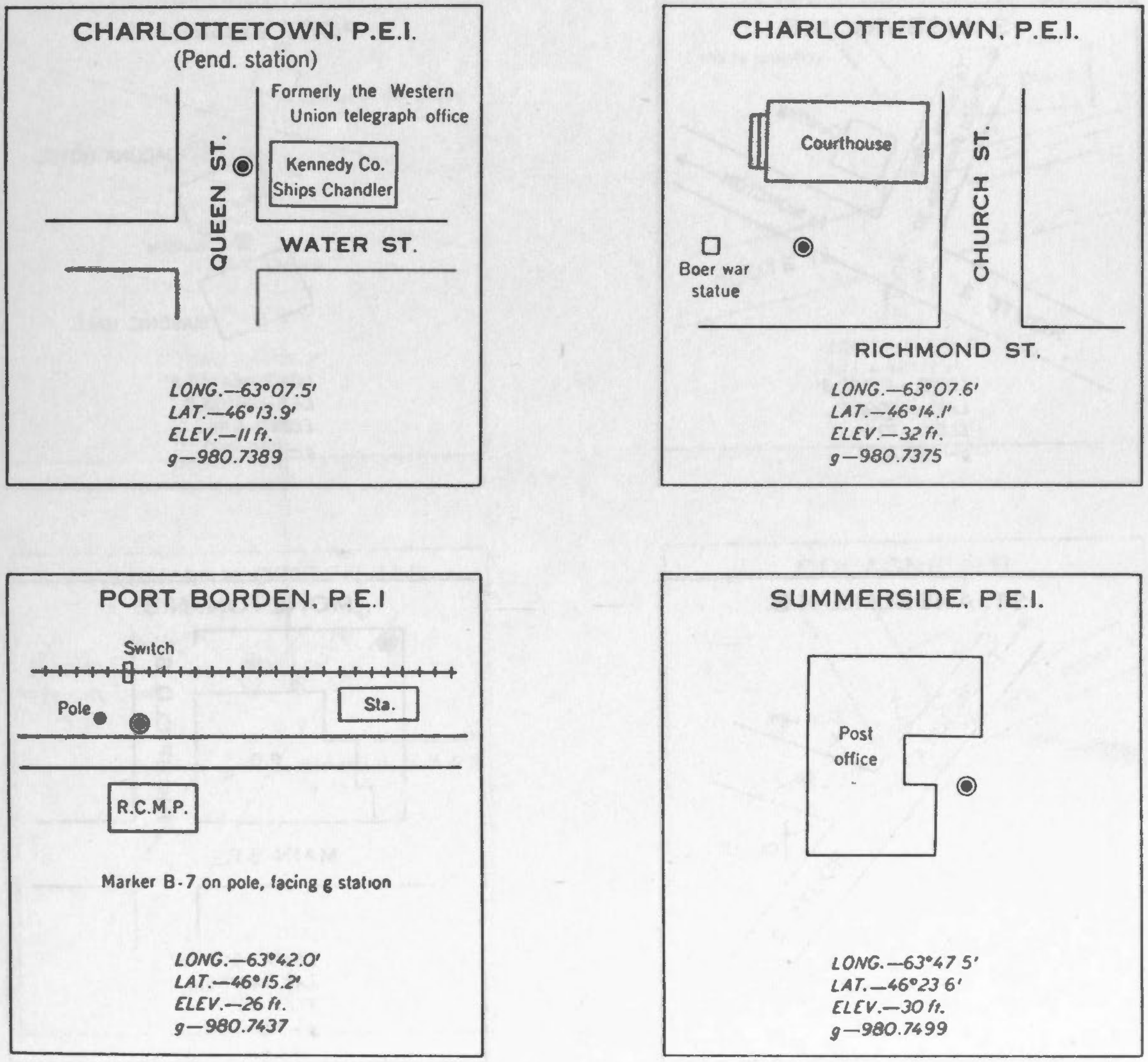


FIG. 1 (*d*). Location of gravity bases in Nova Scotia.

BASES IN PRINCE EDWARD ISLAND



BASES IN NOVA SCOTIA

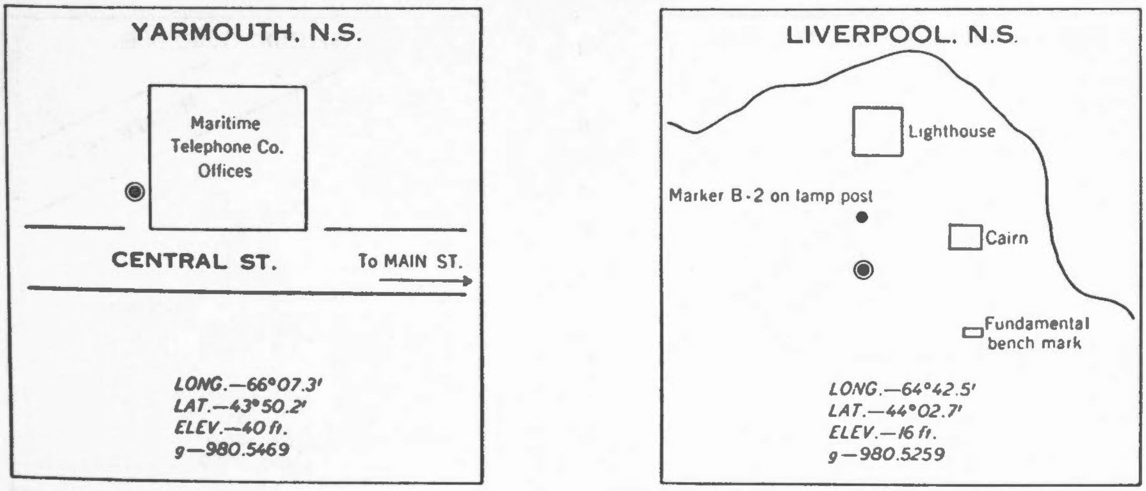


FIG. 1 (e). Location of gravity bases in Nova Scotia and Prince Edward Island.

BASES IN NEW BRUNSWICK

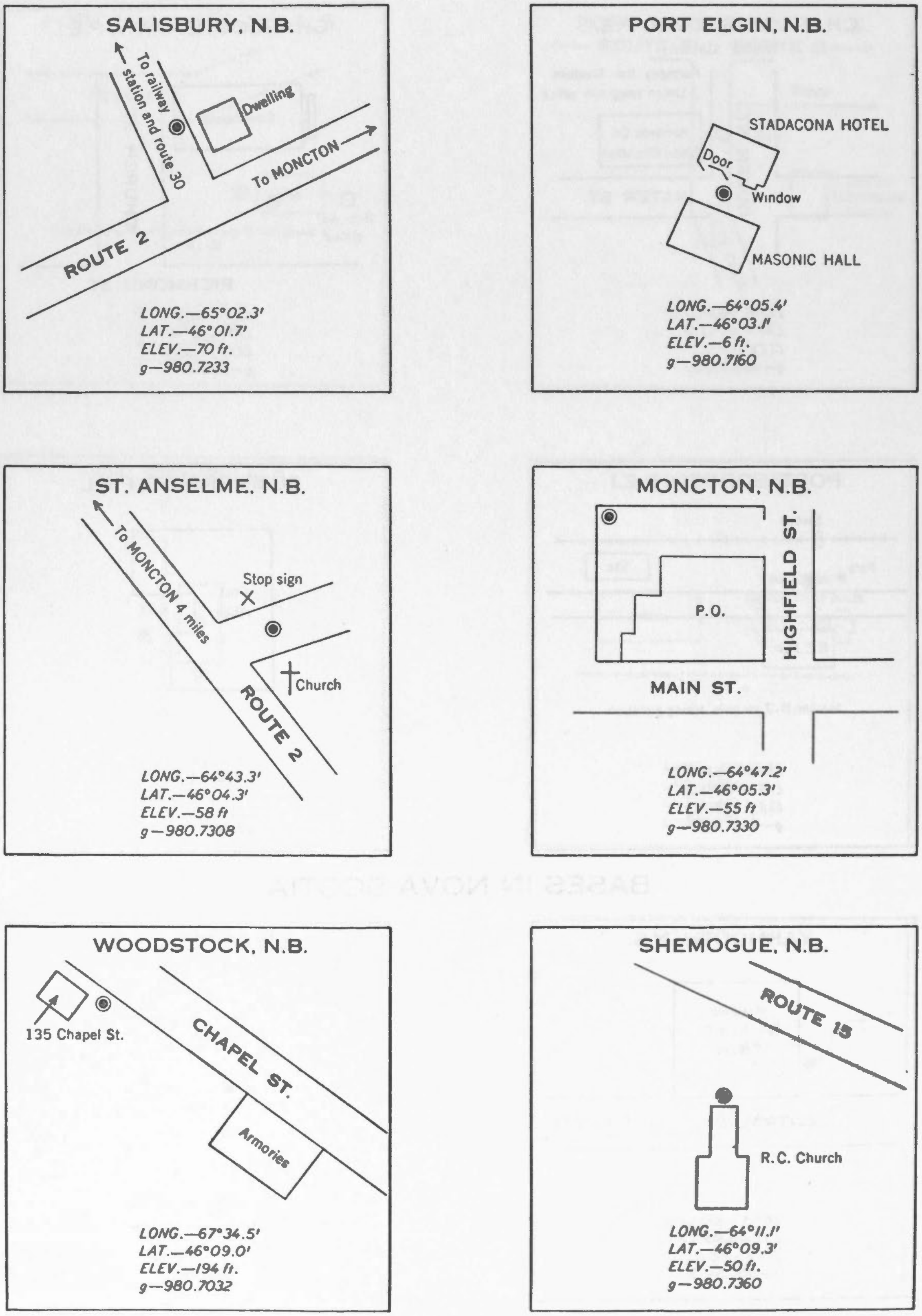
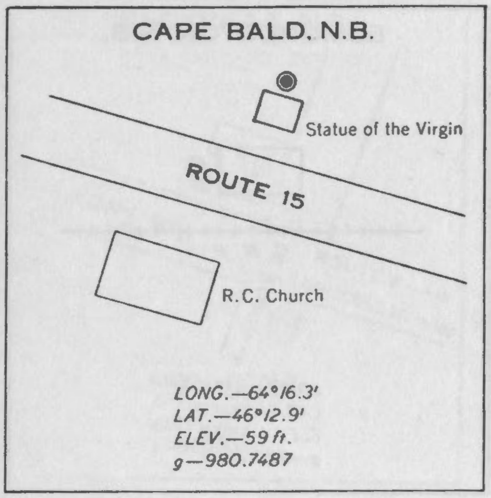
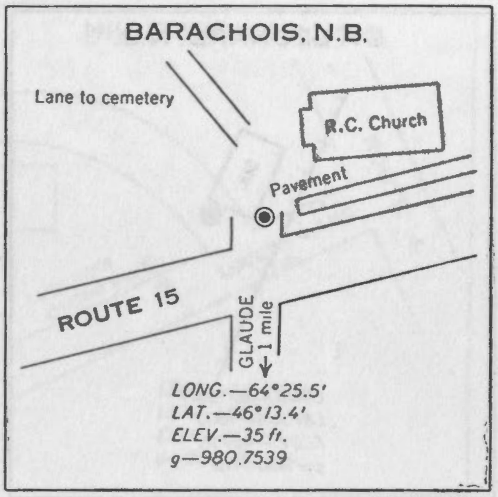
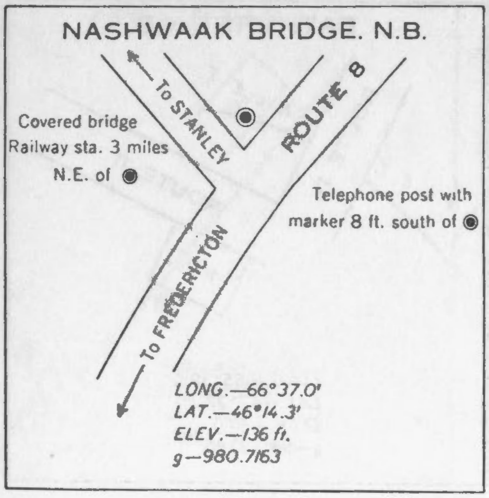


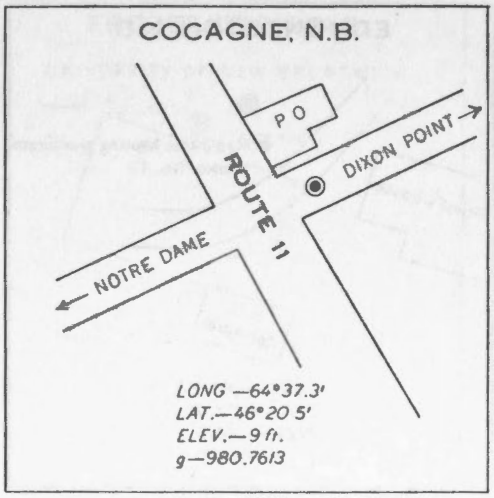
FIG. 1 (*f*). Location of gravity bases in New Brunswick.

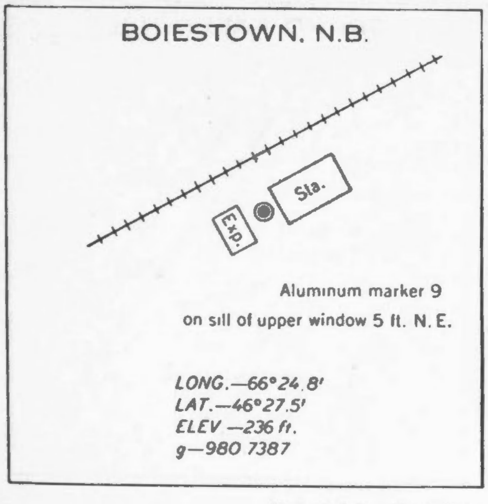
BASES IN NEW BRUNSWICK











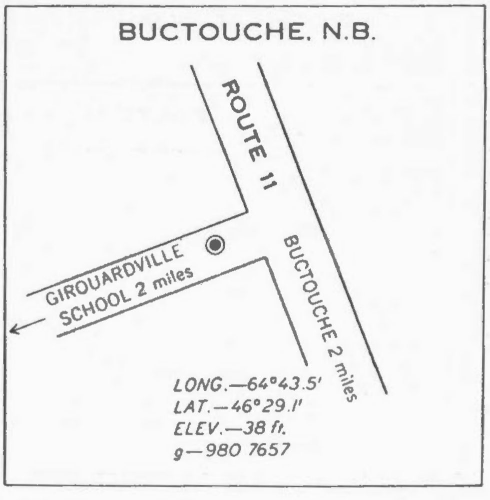


FIG. 1 (*g*). Location of gravity bases in New Brunswick.

BASES IN NEW BRUNSWICK

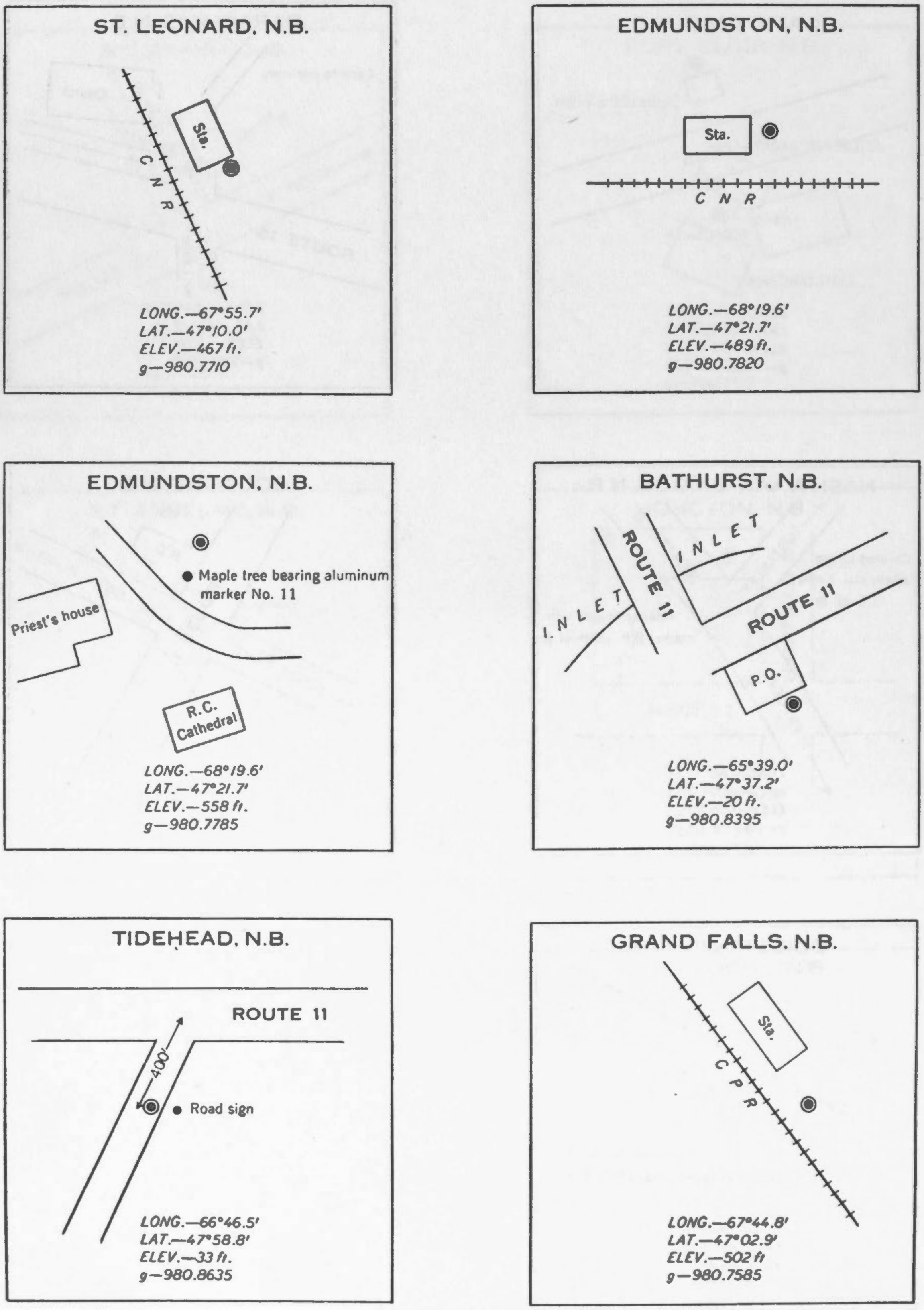
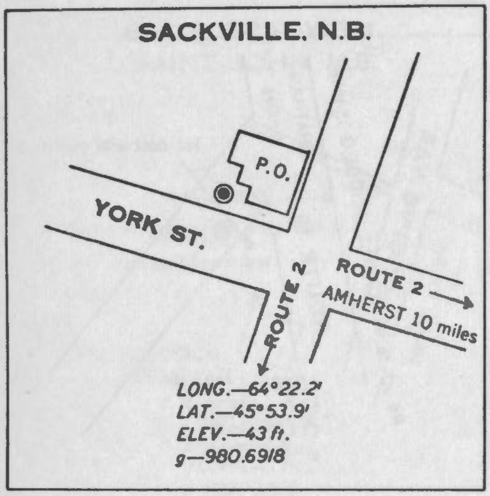


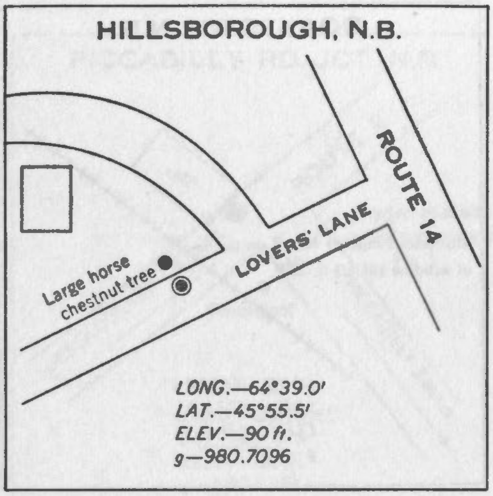
FIG. 1 (*h*). Location of gravity bases in New Brunswick.

BASES IN NEW BRUNSWICK



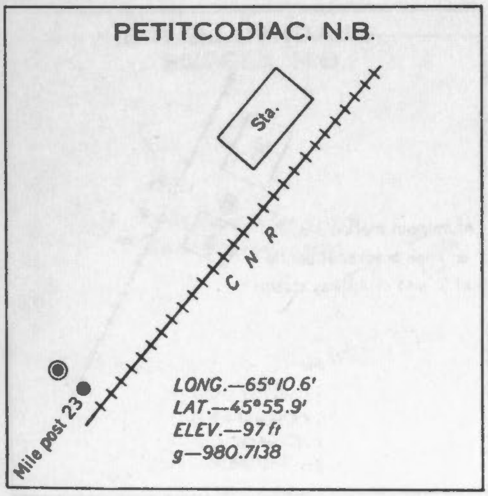
SACKVILLE, N.B.

LONG.—64°22.2′
LAT.—45°53.9′
ELEV.—43 ft.
g—980.6918



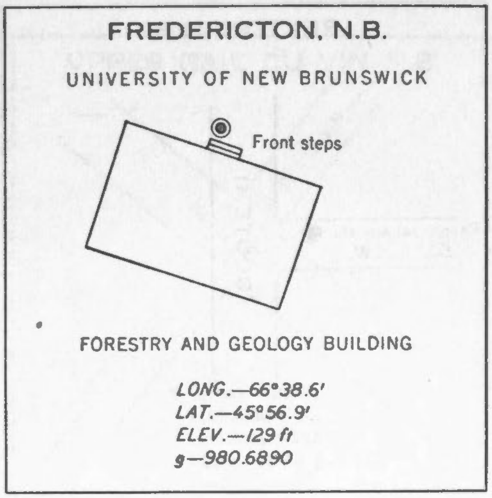
HILLSBOROUGH, N.B.

LONG.—64°39.0′
LAT.—45°55.5′
ELEV.—90 ft.
g—980.7096



PETITCODIAC, N.B.

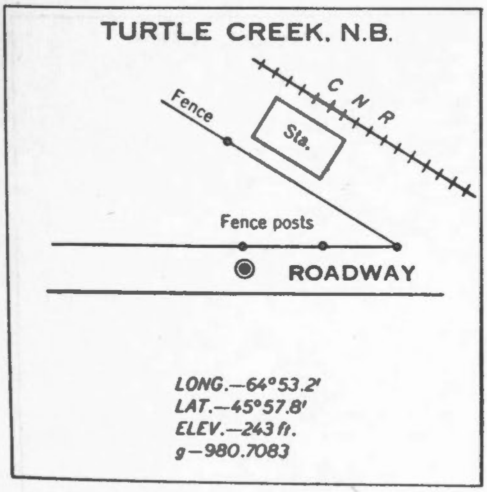
LONG.—65°10.6′
LAT.—45°55.9′
ELEV.—97 ft
g—980.7138



FREDERICTON, N.B.

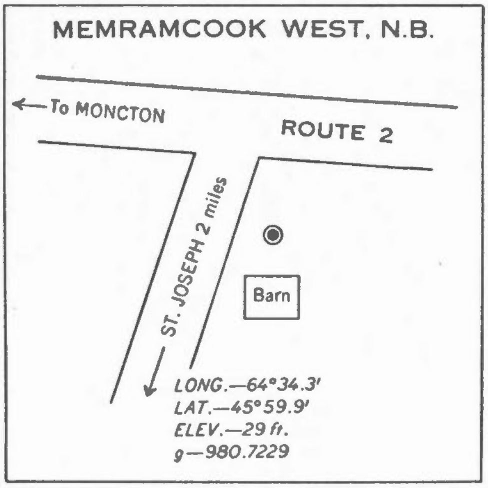
UNIVERSITY OF NEW BRUNSWICK

LONG.—66°38.6′
LAT.—45°56.9′
ELEV.—129 ft
g—980.6890



TURTLE CREEK, N.B.

LONG.—64°53.2′
LAT.—45°57.8′
ELEV.—243 ft.
g—980.7083



MEMRAMCOOK WEST, N.B.

LONG.—64°34.3′
LAT.—45°59.9′
ELEV.—29 ft.
g—980.7229

FIG. 1 (*i*). Location of gravity bases in New Brunswick.

BASES IN NEW BRUNSWICK

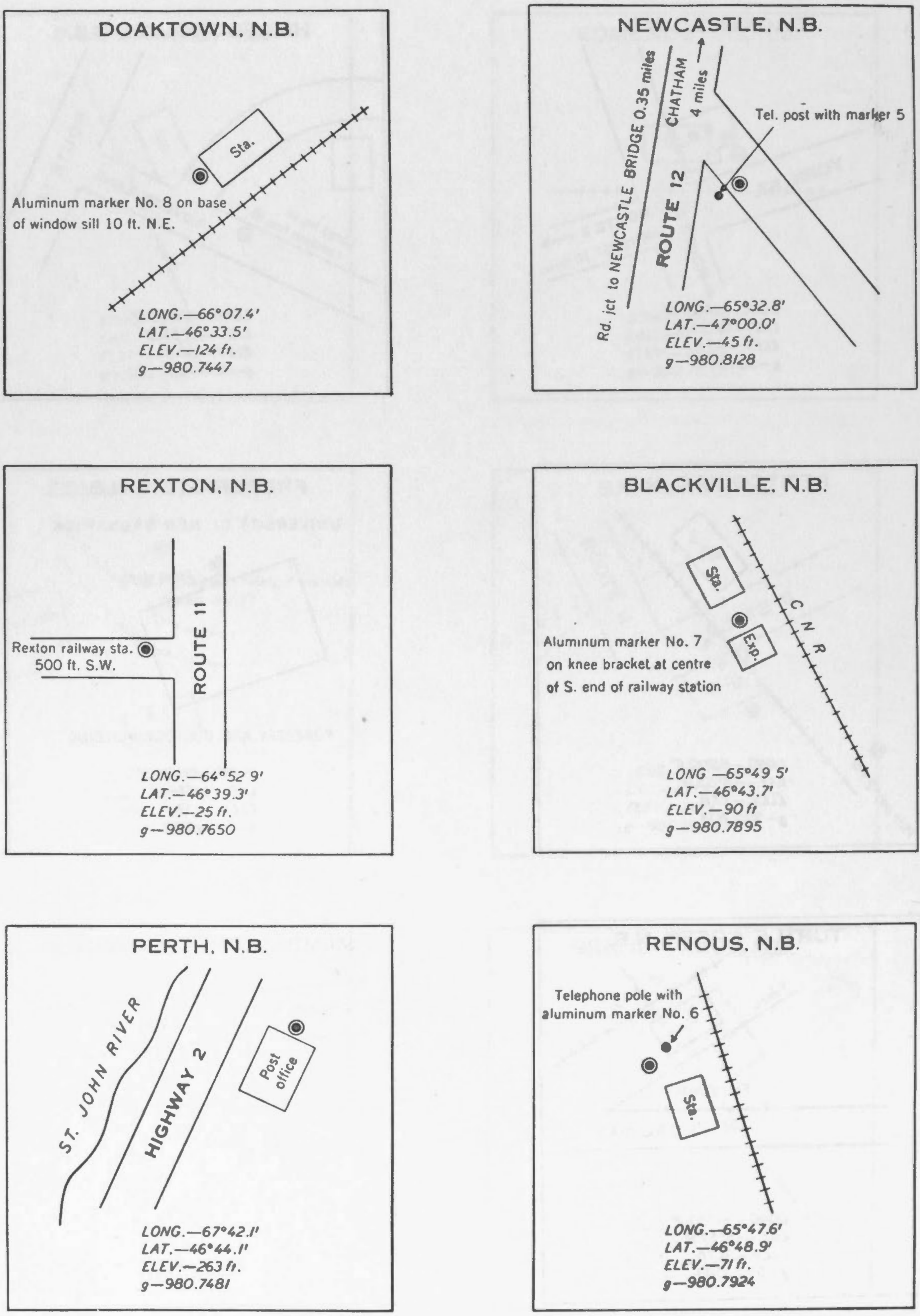
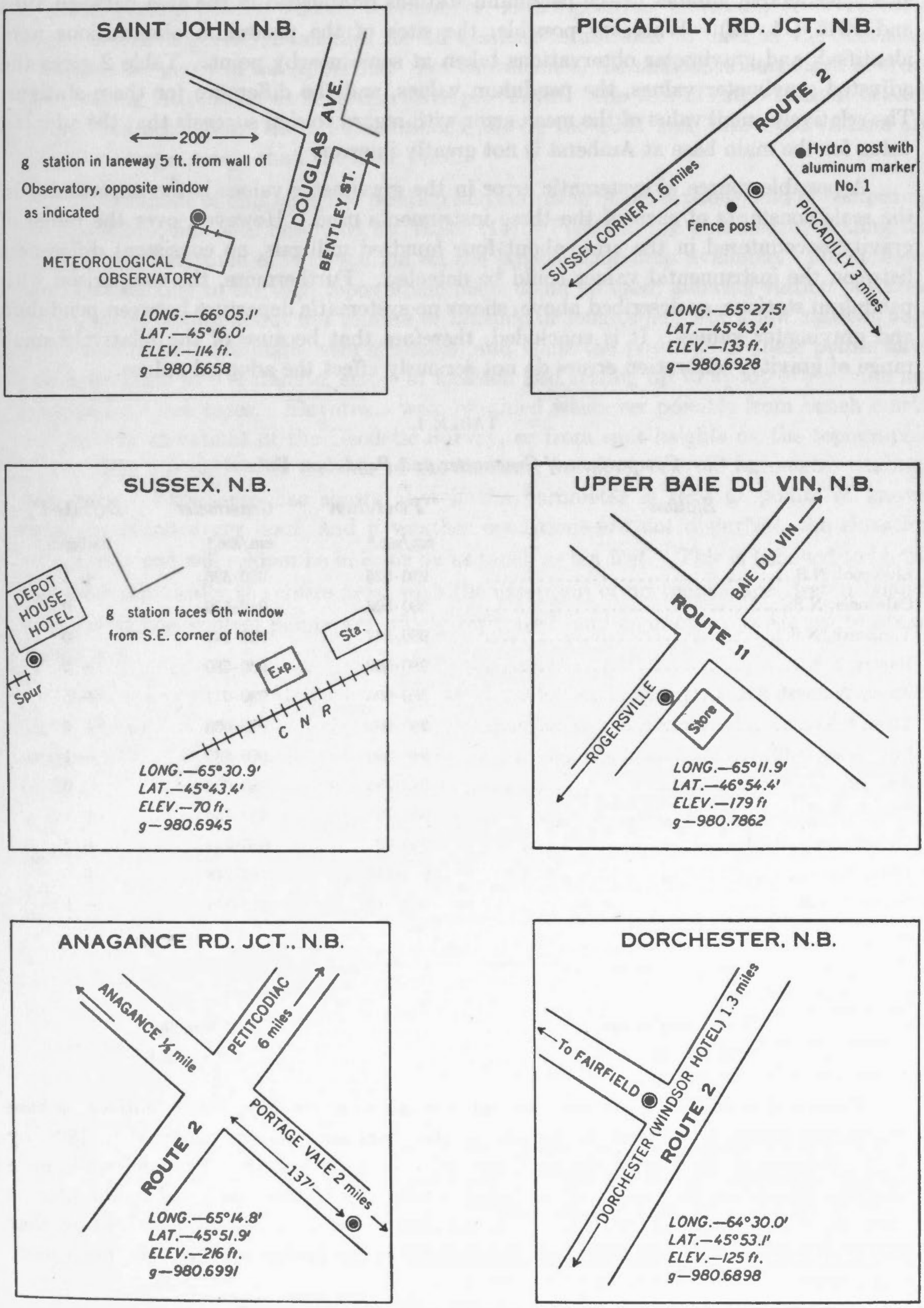


FIG. 1 (*j*). Location of gravity bases in New Brunswick.

BASES IN NEW BRUNSWICK



SAINT JOHN, N.B.

PICCADILLY RD. JCT., N.B.

SUSSEX, N.B.

UPPER BAIE DU VIN, N.B.

ANAGANCE RD. JCT., N.B.

DORCHESTER, N.B.

FIG. 1 (*k*). Location of gravity bases in New Brunswick.

An interesting comparison may be made between gravimeter and pendulum values at a considerable number of the pendulum stations established in the area between 1914 and 1946 (11, 12). Wherever possible, the sites of the pendulum observations were identified, and gravimeter observations taken at some nearby point. Table 2 gives the adjusted gravimeter values, the pendulum values, and the difference for these stations. The relatively small value of the mean error with regard to sign suggests that the adopted value for the main base at Amherst is not greatly in error.

A possible source of systematic error in the gravimeter values is the uncertainty in the scale constants of each of the three instruments used. However, over the range of gravity encountered in the area, about four hundred milligals, no consistent differences between the instrumental values could be detected. Furthermore, the comparison with pendulum stations, as described above, shows no systematic departure between pendulum and gravimeter values. It is concluded, therefore that because of the relatively small range of gravity, calibration errors do not seriously affect the adopted values.

TABLE 1.

Comparison of Gravimeter and Pendulum Values

Station	*Pendulum* cm/sec.^{2}	*Gravimeter* cm/sec.^{2}	*Dif. (G-P)* milligals
Liverpool, N.S.	980·525	980·526	+ 1
Caledonia, N.S.	980·526	980·526	0
Yarmouth, N.S.	980·547	980·547	0
Halifax, N.S.	980·582	980·580	− 2
Annapolis Royal, N.S.	980·606	980·611	+ 5
Truro, N.S.	980·666	980·668	+ 2
Fredericton, N.B.	980·690	980·689	− 1
Amherst, N.S.	980·693	980·693	0
Sydney, N.S.	980·735	980·736	+ 1
Charlottetown, P.E.I.	980·737	980·739	+ 2
Perth, N.B.	980·747	980·748	+ 1
Bathurst, N.B.	980·840	980·839	− 1

Mean Differences:

With regard to sign	+ 0·5 milligal
Without regard to sign	1·2 milligals

Finally, it is interesting to note the value obtained at Sydney, Nova Scotia, at a base established within a few feet of the site of the pendulum station occupied in 1896 by G. R. Putnam of the United States Coast and Geodetic Survey. Putnam, while on a scientific expedition to Greenland, obtained a value for Sydney (referred to the present value at Washington) of 980·737. The gravimeter value is 980·7371, indicating that certain comparatively early pendulum determinations are no less reliable than much more recent ones.

PRINCIPAL FACTS FOR GRAVITY STATIONS

The principal facts, that is, the number, name, position, elevation, observed value of gravity, and gravity anomalies for all stations established to date in the Maritime Provinces are given in the Appendix. For convenience, the stations are arranged in order of increasing latitude for each of the three provinces. The year of establishment of each station has been given since, as mentioned above, the 1944 and 1945 observations are subject to larger errors than the later work.

The methods of obtaining the position and elevation of the stations, and of computing the anomalies, has been described by Miller (14). Positions are obtained by scaling the latitude and longitude of each station on the largest scale map available. For most of the area one mile to the inch topographic maps could be used, allowing station positions to be located within about 0·1 minute of latitude or longitude. For a few stations only eight mile to the inch maps were available, and while the positions of these points have also been given to 0·1 minute, errors of location and scaling up to about 0·5 minute are possible for these cases. Elevations were obtained whenever possible from bench marks and railway elevations of the Geodetic Survey, or from spot heights on the topographic maps. For a considerable number of the stations, however, aneroid barometer readings were used. Experience has shown that if the barometer is read at points of known elevation about every hour, and if weather conditions are not disturbed, the elevation values obtained will seldom be in error by as much as ten feet. This is believed to be the case over practically the entire area, with the exception of northern Cape Breton Island, where elevation control points are widely separated, and errors may range up to about fifteen feet.

Theoretical gravity at sea level (γ_0) is given for each station, as interpolated from the tables of Swick (22)*. Free air and Bouguer values of computed gravity have been obtained by applying the respective corrections to the sea-level value. For the Bouguer correction, a mean density of 2·67 grams per cubic centimetre has been assumed for the rock above sea level for the entire area. It will be shown in a later chapter that in fact there is considerable variation in the density among the rock types present, but the resulting error in the Bouguer anomalies is not large. Most of the highland areas, where stations are at a considerable height above sea level are underlain by rocks having a density close to the assumed value. Conversely, the areas of Carboniferous and later sediments, where the surface density may be 2·50 grams per cubic centimetre or lower, have practically all been eroded to near sea level, so that the Bouguer correction is not large for stations in these areas. It is believed that the Bouguer correction for all stations in the region is accurate to within about one milligal, which is adequate for the study of large, regional anomalies.

While in this paper the Bouguer anomalies are used exclusively for the study of geological features, the tables of Principal Facts give also the free air anomalies, because of their use in determining deflections for the vertical and the undulations of the geoid.

---

* It should be noted in passing that the International Gravity Formula as formally adopted, and as tabulated by Swick, differs slightly from the table of Lambert and Darling (9), which was reproduced by Nettleton (15). The discrepancy is not apparent, however, when values are quoted to 10^{-4} c.g.s. units only.

OUTLINE OF THE MAJOR GEOLOGICAL STRUCTURES OF THE REGION

It is proposed in this section to outline very briefly the structural history of the region, merely to acquaint the reader with the features which will be discussed in detail in the interpretations which follow. As a result of over a century of work by geologists of the Geological Survey of Canada, and others, a vast amount of material has been built up on the geology of the region. Still, it may safely be said that not all the relationships are completely understood.

Early Precambrian rocks are found in two widely separated localities in the area. The George River series in Cape Breton Island (26), comprises crystalline limestone, quartzite, hornfelsic shale, and greywacke, and is extensively cut by igneous intrusions. In southwestern New Brunswick, rocks of similar lithology and relationships are known as the Green Head group (1). The areal extent of these rocks is not great, and they are of little importance in the present interpretation of the larger gravity anomalies.

Of more importance are rocks believed to be of Proterozoic (late Precambrian) age, which occur extensively on the Nova Scotia mainland and in more limited areas in southeastern Cape Breton and southern New Brunswick. Faribeault (10) has studied in detail the Meguma series of slates and quartzite, which underlie much of southern Nova Scotia, and has estimated their thickness to be in excess of 30,000 feet. Proterozoic volcanic rocks known as the Coldbrook group underlie the prominent Caledonia highlands of southern New Brunswick, and similar, but not necessarily equivalent, rocks known as the Fourchu group, occur in southeastern Cape Breton.

The Palæozoic is well represented throughout the area. Cambrian rocks have been identified in Cape Breton and near Saint John, New Brunswick. Ordovician strata are well displayed west of Antigonish (24) and over much of northwestern New Brunswick. At the close of the Ordovician period, the region was involved in the Taconic disturbance, and the existing rocks were faulted and folded.

Silurian and Lower Devonian strata in Nova Scotia and New Brunswick are evidence of the reduction of the Taconic mountains during the Silurian period, and of the submergence of parts of the region during these times. During Middle Devonian time the region underwent the Acadian orogeny and many of the relationships developed during this disturbance are of importance in the study of the gravity anomalies. Preexisting rocks were folded, faulted and invaded by large masses of granite. One large, lobster-shaped batholith occupies the heart of southern Nova Scotia. A line of similar granitic intrusions trends northeasterly across New Brunswick. The Devonian intrusions of Nova Scotia have been described by Faribeault as being of two types. The older and more widespread type is a coarse-grained biotite granite or granodiorite, while the younger is a fine-grained muscovite granite. These rocks were probably intruded at considerable depth, and erosion of much overlying rock occurred in post-Devonian time. Apparently, this erosion was largely accomplished during the late Devonian, as the lowest Mississippian beds, the Horton group, rest on the denuded granite surface. The features developed during the Acadian disturbance are prominent in the Maritimes today because no later disturbance has affected the region as a whole. This fact has been pointed out by Schubert (20).

Following the erosion of late Devonian time, and the deposition of the earliest Carboniferous rocks, warping of the crust produced troughs, and invasion by the sea occurred. This is evidenced today by the Upper Mississippian Windsor group which is mainly composed of limestone, salt, gypsum and marine shale. The Windsor series was deformed prior to the deposition of the Pennsylvanian sediments, but according to Bell (3), much of this deformation was in the nature of differential warping, rather than folding by horizontal forces.

Pennsylvanian continental beds form a blanket over much of northern Nova Scotia, eastern New Brunswick and Prince Edward Island. Typical rocks of this sub-system are red or grey sandstones, shales and conglomerates, with coal measures occurring in three groups of different ages. The strata are in general either flat lying or gently folded; thus the Appalachian disturbance, at the end of the Palæozoic era, had relatively minor effects in the Maritime region.

The youngest consolidated sediments known in the region are of Mesozoic age and are referred to the Triassic. These are found on both sides of the Bay of Fundy but are particularly extensive in Nova Scotia. According to Powers (17), who has made a detailed study of the Triassic of this region, the deposits which remain are remnants from a large area of such beds, which occupied most of the present Bay of Fundy. Basic lavas were extruded during the time of Triassic sedimentation, and these, because of their greater resistance to erosion, form prominent topographic features along the shores of the Bay of Fundy.

Faulting has played an important part in the development of the structural features of the Maritimes, especially of Nova Scotia. Cameron (4) has recently grouped the faults of the latter province into those of three main periods. The first of these is post-Lower Devonian, pre-Carboniferous, and the faults are probably related to the Acadian disturbance of the Middle Devonian. Faults cutting the Meguma sediments and Devonian granite masses are very numerous, but three faults of the period are particularly notable for their length. The first of these is the Hollow fault, stretching from near New Glasgow northeast to Cape George and perhaps beyond. The upthrow side of this fault is to the southeast. To the west of the Hollow fault is the Cobequid fault, which extends from Cape Chignecto eastward to the general area of New Glasgow. Indeed, the Cobequid and Hollow faults may form one continuous structure over one hundred and fifty miles long. The upthrow side of the Cobequid fault is to the north, and comprises the uplands known as the Cobequid Mountains. This would imply a hinge relation between the Cobequid and Hollow faults, with the hinge point lying in the neighbourhood of New Glasgow. The third major fault strikes northeasterly across northern Cape Breton Island for, according to Cameron, a distance of sixty-five miles.

The second general period of faults is of post-Pennsylvanian age. Numerous faults of this age are known in the coal fields of Inverness and Sydney on Cape Breton Island, and in the Pictou coal field, where a graben has been formed. Bell (3) has shown that many of the exposures of Lower Carboniferous rocks in northern Nova Scotia are upfaulted blocks, brought into contact with Upper Carboniferous formations. Further movement on the Cobequid fault also occurred at this stage, for Weeks (23) has described evidence of post-Carboniferous faulting along the southern margin of the Cobequid Mountains.

Finally, a third period of faulting took place some time after the Triassic. Much of the Triassic of the Maritimes is cut by faults, mostly normal, which produce fault blocks and local grabens. Cameron has suggested that many of the post-Pennsylvanian and post-Triassic faults may be merely the surface expression of recurring movement between a series of fundamental fault blocks produced during the Acadian disturbance. Whether or not this is so is an unsolved problem of the geology of the Maritimes, but it can be said that the faults most strikingly reflected in the gravity picture are the Cobequid and Hollow faults, two faults of what is apparently the earliest period.

INTERPRETATION OF GRAVITY ANOMALIES

The accompanying map of Bouguer gravity anomalies* will indicate the main features to be discussed in this section. Many of these have already been pointed out by Miller (15), but before studying individual anomalies in detail, it will be well to consider the general nature of the pattern over the complete region. The Atlantic shore of mainland Nova Scotia is seen to be an area of generally negative anomaly, bounded to the west and north by the positive anomalies which follow the Fundy shoreline and the Cobequid Mountains. The negative anomaly reaches its greatest amplitude of -60 milligals in the neighbourhood of New Ross, approximately in the centre of the largest exposure of Devonian granite. Extensions of the low to north and south generally follow the granite bodies, but axes of the gravity "troughs" are sometimes displaced from the surface exposures of granite, as in the case of the low west of Liverpool. Areas of less intense negative anomaly are present in the Minas Basin area, and in the lowlands of central Cape Breton Island.

The positive anomalies to the north and west of the negative belt are found in isolated areas, such as the Digby-Yarmouth region of southern Nova Scotia, the Caledonian highlands of New Brunswick, the Cobequid and Antigonish highlands of northern Nova Scotia, the highlands of Cape Breton Island, and a narrow strip of western Prince Edward Island. To the northwest of these areas, negative anomalies are again seen covering most of northern New Brunswick and Prince Edward Island. These negative anomalies reach their greatest amplitude to the west of the map area, in the vicinity of the Devonian granite intrusions west and northwest of Fredericton.

The general pattern of anomalies may thus be summarized by noting that negative anomalies tend to occur over or in close proximity to, masses of Devonian granite, and also over basins of Carboniferous sediments, while positive anomalies are found over areas of other pre-Carboniferous rocks. It is to be noted that the isolated positive anomalies, mentioned above, could form one continuous band across the region, were it not for the effects of local sedimentary basins, such as the Minas Basin area of Triassic sediments, and the Cumberland Basin north of the Cobequid Mountains. These qualitative correlations of positive and negative anomalies with rock types have now to be tested by quantitative studies of specific anomalies.

---

* The quantities plotted on the map are in units of 1×10^{-4} c.g.s., or tenths of milligals. Contours are drawn at intervals of 100 of these units, or ten milligals.

NOVA SCOTIA

Anomalies Associated with the Granitic Intrusions of Southern Nova Scotia

The general coincidence of negative anomalies with the larger granite masses of southern Nova Scotia, together with the steep gravity gradients observed in many instances over the contact of the granite with the metamorphosed sediments, strongly suggest that the granite itself is responsible for at least a part of the negative anomalies. Density determinations on samples of the various rock types definitely support this hypothesis, although it must be admitted that the number of determinations made was probably insufficient to give a truly representative density to each formation. This is especially true of the Devonian intrusive rocks, as they cover an area of many hundreds of square miles, and are variable in composition. Nevertheless, samples of the granites from both Nova Scotia and New Brunswick were found to have densities which ranged between the limits of 2·60 and 2·65 grams per cubic centimetre. By comparison, densities of samples of the Meguma series of slates and quartzites ranged from 2·70 to 2·75 grams per cubic centimetre, with the slates in general being more dense. It would appear from these determinations that a density contrast of the order of 0·1 gram per cubic centimetre could be assumed between the granite and the surrounding Precambrian rocks. The refinement of this figure will require many more density measurements, but it is safe to say that it could hardly be increased significantly, first because the mean density of the Precambrian rocks is probably closer to 2·70 than to 2·75 (as quartzite is more abundant than slate in the series), and secondly because there have been very few granites reported with densities less than 2·60.

The pattern of negative anomalies in southern Nova Scotia indicates a major structure in the neighbourhood of New Ross, where the greatest minimum of less than −50 milligals occurs. The minimum is roughly circular in plan, suggesting that the anomalous body could be approximated by a vertical cylinder. As a matter of fact, a vertical cylinder thirty-six miles in diameter extending eighteen miles in depth partially satisfies the observed anomaly as shown by the calculated profile in Figure (2).

The cylinder fails to explain the extensive areas of more moderate negative anomaly (− 10 to − 30 milligals), to the northeast and southwest of the major anomaly. These areas could be caused by a sheet-like mass of granite underlying the Meguma series over a broad area. For a negative anomaly of 20 milligals, a sheet with a thickness of three miles is required, as calculated by the simple Bouguer formula. The structure sections and profile (Figure 3) show the final form of the granite body as deduced from the gravity anomalies. It will be observed that the areas of Meguma sediments, presumably in the form of roof pendants, produce local highs within the general region of negative anomalies.

To complete the synthesis of the anomaly-producing body, the boundaries of the sheet-like mass will be indicated, where possible. Along the south and southeast shore of Nova Scotia the negative anomalies appear to continue outward over the ocean. In this direction, therefore, the boundary of the sheet must be beyond the coastline. To the west, and northwest, the area of negative anomaly terminates in a steep rise to positive values of 10 to 20 milligals. Profiles of the gravitational effect across known contacts of the granite with the Meguma series in the area south of Digby (Figure 3) show that the contact is indicated satisfactorily by the inflection point of the profile. Furthermore, comparisons of these profiles with the calculated effects of vertical contacts suggest that the actual contacts are steep. It is concluded that the area underlain by granite is fairly sharply bounded along the west and northwest, except in one area near Bridgetown, where both geological evidence and the gravity contours suggest an extension of the granite under the Bay of Fundy.

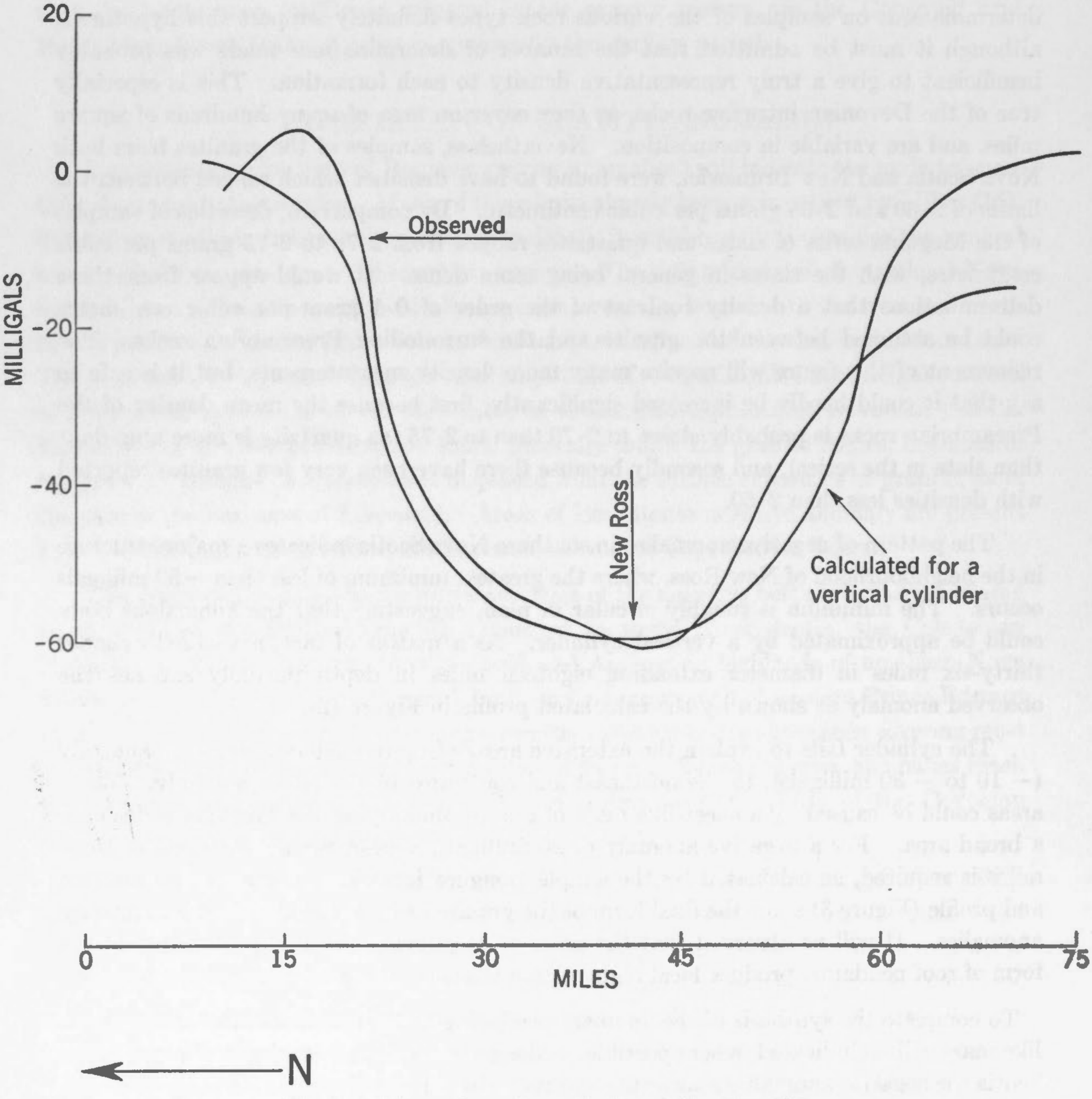


FIG. 2. North-south gravity profile through New Ross, N.S.

The interpretation offered for the negative anomalies of southern Nova Scotia, therefore, is that the individual, scattered exposures of Devonian granite throughout the area are but the surface expressions of a much larger, connected mass which underlies,

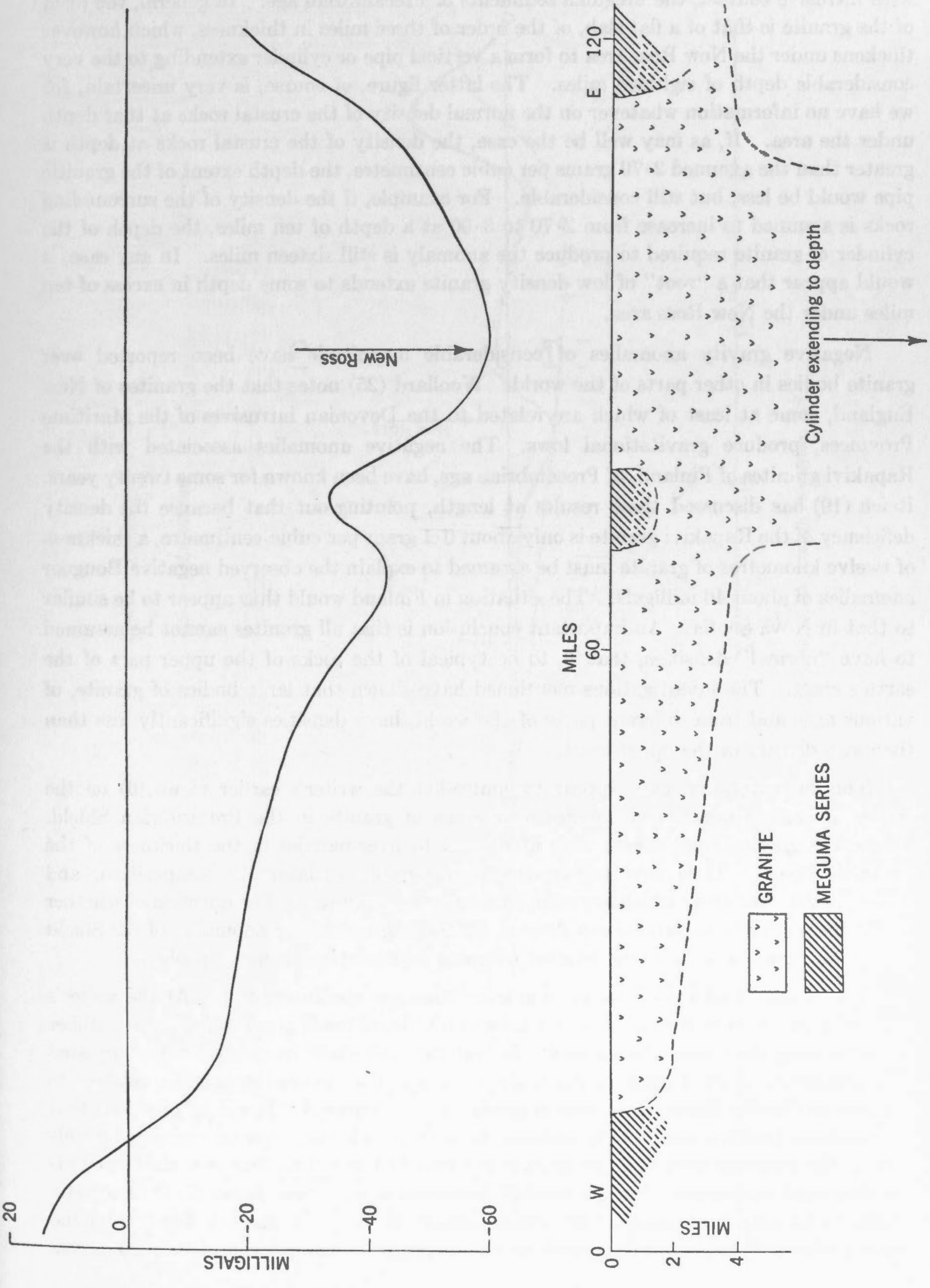


Fig. 3. East-west gravity profile through New Ross, N.S.

with intrusive contact, the Meguma sediments of Precambrian age. In general, the form of the granite is that of a flat slab, of the order of three miles in thickness, which however thickens under the New Ross area to form a vertical pipe or cylinder extending to the very considerable depth of eighteen miles. The latter figure, of course, is very uncertain, for we have no information whatever on the normal density of the crustal rocks at that depth under the area. If, as may well be the case, the density of the crustal rocks at depth is greater than the assumed 2·70 grams per cubic centimetre, the depth extent of the granitic pipe would be less, but still considerable. For example, if the density of the surrounding rocks is assumed to increase from 2·70 to 3·00 at a depth of ten miles, the depth of the cylinder of granite required to produce the anomaly is still sixteen miles. In any case, it would appear that a "root" of low density granite extends to some depth in excess of ten miles under the New Ross area.

Negative gravity anomalies of considerable magnitude have been reported over granite bodies in other parts of the world. Woollard (25) notes that the granites of New England, some at least of which are related to the Devonian intrusives of the Maritime Provinces, produce gravitational lows. The negative anomalies associated with the Rapakivi granites of Finland, of Precambrian age, have been known for some twenty years. Reich (19) has discussed these results at length, pointing out that because the density deficiency of the Rapakivi granite is only about 0·1 gram per cubic centimetre, a thickness of twelve kilometres of granite must be assumed to explain the observed negative Bouguer anomalies of about 40 milligals. The situation in Finland would thus appear to be similar to that in Nova Scotia. An important conclusion is that all granites cannot be assumed to have "normal" densities, that is, to be typical of the rocks of the upper part of the earth's crust. The investigations mentioned have shown that large bodies of granite, of various ages and from different parts of the world, have densities significantly less than the mean density of the upper crust.

This interpretation may appear to contradict the writer's earlier views (6) on the causes of certain negative anomalies over areas of granite in the Precambrian Shield. There, the gravitational effects were attributed to irregularities in the thickness of the "granitic layer". It is now known that considerable variation in composition, and density, exist over areas which are mapped merely as "granite". The question of whether or not these density variations can account for the more extensive anomalies of the Shield cannot be answered until more detailed mapping and sampling is accomplished.

The magnetic effects of the main granite mass are also interesting. At the writer's request, a party from the Nova Scotia Research Council made observations at a number of points along the Chester Basin-Kentville highway, using a Watt magnetometer adjusted to a sensitivity of 22·2 gammas per scale division. The reduced anomalies, relative to the base at Chester Basin, are shown in profile form in Figure 4. It will be observed that the magnetic profile is surprisingly uniform, for a traverse largely over outcropping igneous rock. The anomaly level over the granite is definitely lower than that over the surrounding slates and quartzites. Using a method developed in a previous paper (7) the magnetic profile to be expected from uniform magnetization of the body was calculated from the gravity observations, and is indicated on the diagram. A comparison of the two curves

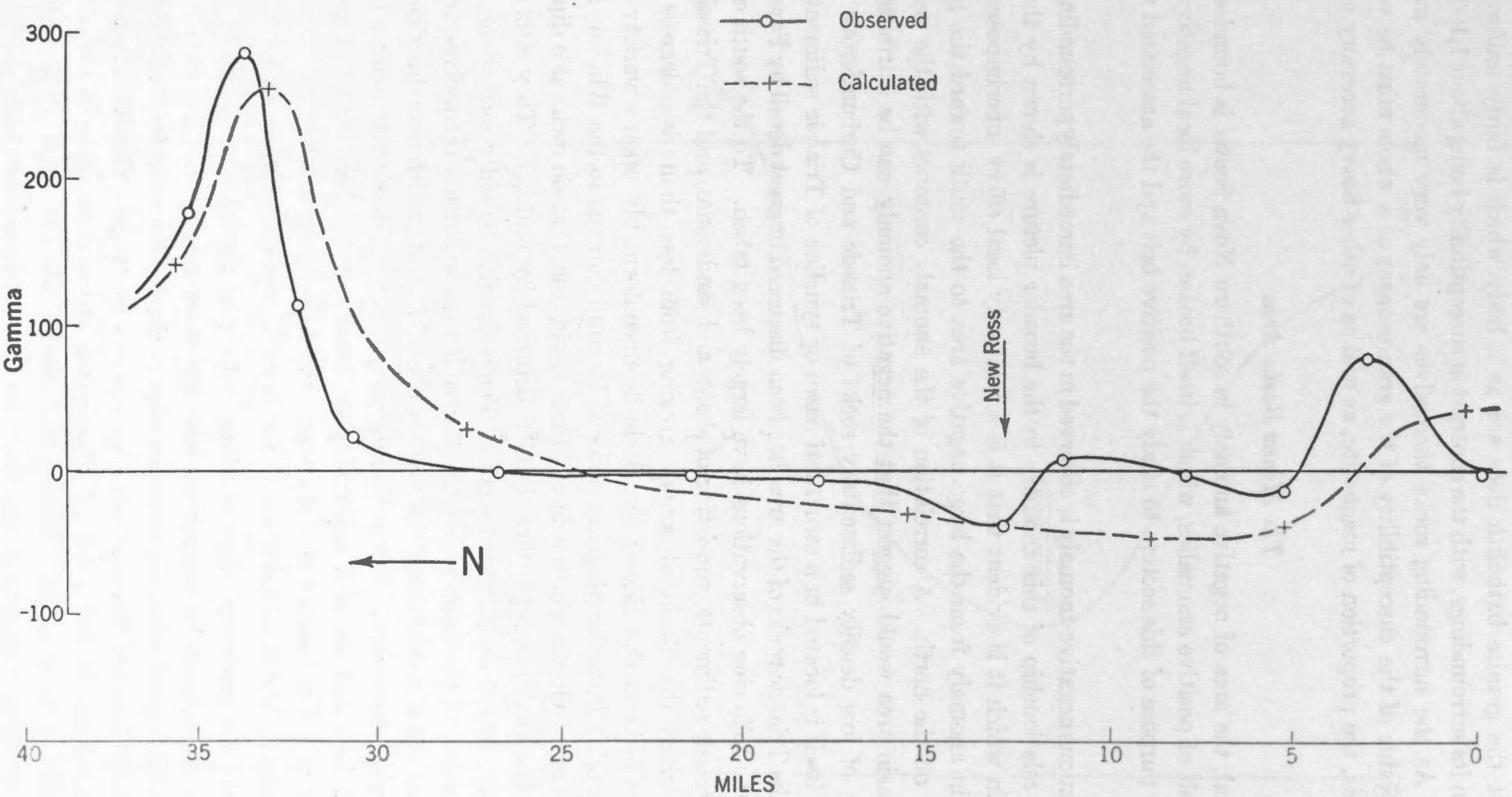


FIG. 4. North-south magnetic profile through New Ross, N.S.

indicates that the granite batholith does act as a body which is fairly uniformly less magnetic than its surroundings, with the contrast in susceptibility being about $1{,}100 \times 10^{-6}$ c.g.s. units. As the surrounding rocks themselves are only very moderately magnetic, the absolute value of the susceptibility of the granite mass as a whole must be very low. In other words, the proportion of magnetite, as well as of other heavy accessory minerals, must be low.

The Minas Basin Area

In general, the area of negative anomaly in southern Nova Scotia is bounded on the north by a belt of positive anomalies, which is itself broken by more local negative effects. It will be the purpose of this section to study the positive belt and the associated negative anomalies.

A conspicuous negative anomaly is observed in the area immediately surrounding Minas Basin. The relationship of this anomaly to the broader picture is shown by the profile of Figure 5, in which it is evident that it is a relatively local effect superimposed on the gradual rise in anomaly from the large negative area to the south toward the generally positive area on the north. A correlation of the anomaly contours with the geology of the Minas Basin area would suggest that the negative anomaly can be attributed to an accumulation of low density sedimentary rocks of Triassic and Carboniferous age, for Minas Basin itself is located in a structural basin or syncline of Triassic sediments. The structure of the Triassic rocks of the area has been discussed in great detail by Powers (17), from whom the following observations have largely been taken. To the south of Minas Basin, the Triassic sediments, consisting of shales and sandstones, and the Triassic basalt flows, dip toward the Basin at angles ranging from less than five degrees to ten degrees. The beds on this side of the Basin lie unconformably upon a variety of older formations ranging from the Meguma series of Precambrian age to the Windsor group of Mississippian age. On the north side of Minas Basin, the Triassic rocks also dip toward the Basin at low angles, except where locally disturbed by faulting. They either overlie unconformably, or are downfaulted against, Pennsylvanian or older formations. A few miles to the north of the basin shore, the Carboniferous sediments themselves are downfaulted against older rocks, along the great Cobequid fault, which was described in the general geological discussion. The sedimentary rocks of the Triassic may reach a thickness of over 3,500 feet, and are of a uniformly low density, averaging about 2·4 grams per cubic centimetre. The basalt flows, of course, are much denser, averaging 2·80 grams per cubic centimetre. The total thickness of the flows is probably slightly under 1,000 feet.

In Figure 5 the calculated effect of a long body of triangular cross-section and density contrast of 0·17 is shown for comparison with the observed profile. The fit between the two curves is fairly good when the northern edge of the section is made steeply-dipping to a depth of 15,000 feet, and the southern edge dips at a low angle. This would suggest that several thousand feet of low density Carboniferous strata must underlie the Triassic in the central part of the syncline. Farther east, toward the end of the Basin near Truro, the negative anomaly decreases in amplitude and finally disappears.

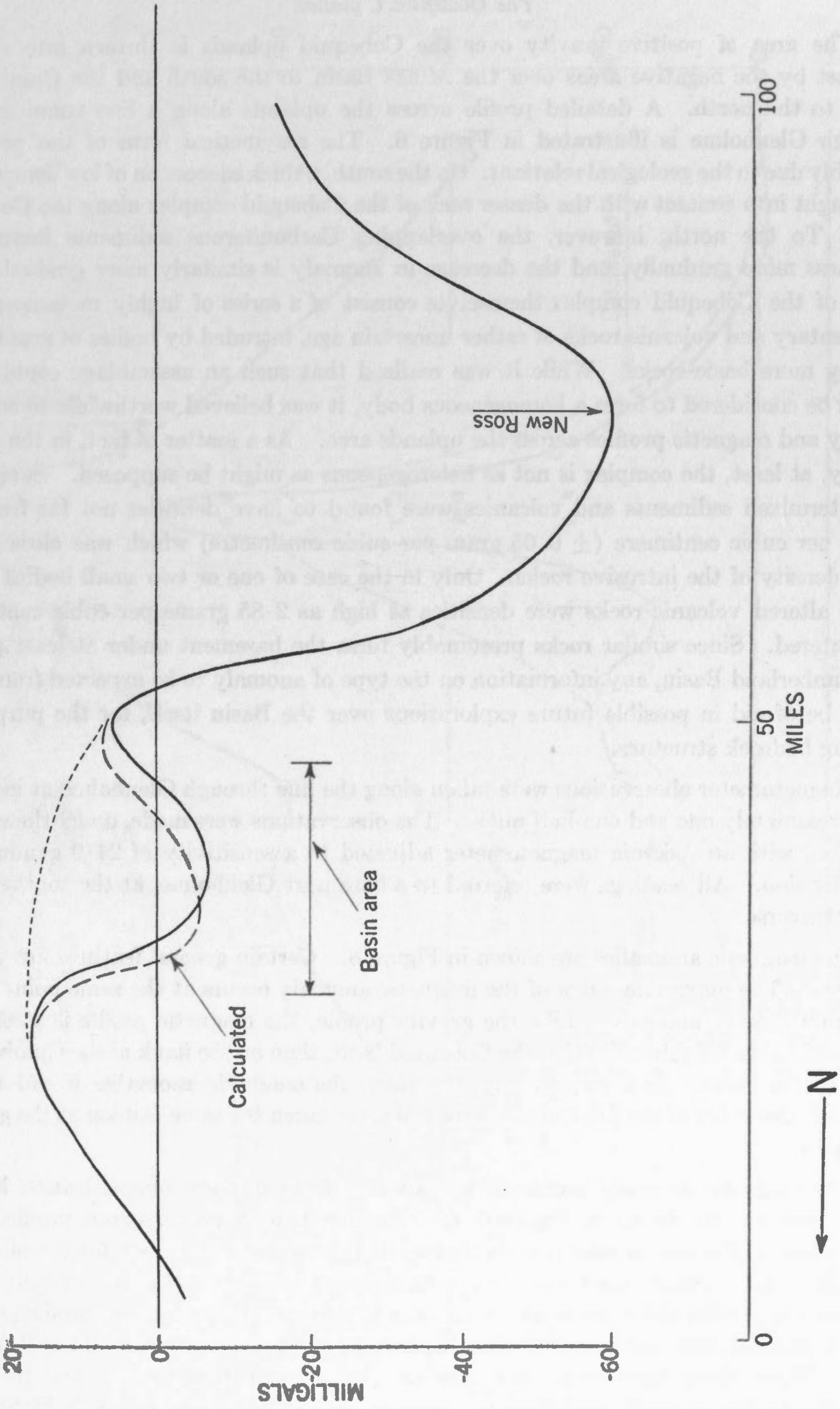


FIG. 5. Observed and calculated gravity profiles across Minas Basin.

The Cobequid Uplands

The area of positive gravity over the Cobequid uplands is thrown into striking contrast by the negative areas over the Minas Basin to the south and the Cumberland Basin to the north. A detailed profile across the uplands along a line running north through Glenholme is illustrated in Figure 6. The assymetical form of the profile is probably due to the geological relations. On the south, a thick succession of low density beds is brought into contact with the denser rock of the Cobequid complex along the Cobequid fault. To the north, however, the overlapping Carboniferous sediments increase in thickness more gradually, and the decrease in anomaly is similarly more gradual. The rocks of the Cobequid complex themselves consist of a series of highly metamorphosed sedimentary and volcanic rocks of rather uncertain age, intruded by bodies of granite and also by more basic rocks. While it was realized that such an assemblage could by no means be considered to form a homogeneous body, it was believed worthwhile to compare gravity and magnetic profiles across the uplands area. As a matter of fact, in the case of density, at least, the complex is not as heterogeneous as might be supposed. Samples of the intermixed sediments and volcanics were found to have densities not far from 2·7 grams per cubic centimere (± 0.05 gram per cubic centimetre) which was close to the mean density of the intrusive rocks. Only in the case of one or two small bodies of less highly altered volcanic rocks were densities as high as 2·85 grams per cubic centimetre encountered. Since similar rocks presumably form the basement under at least part of the Cumberland Basin, any information on the type of anomaly to be expected from them would be of aid in possible future explorations over the Basin itself, for the purpose of locating bedrock structure.

Magnetometer observations were taken along the line through Glenholme at intervals of approximately one and one-half miles. The observations were made, under the writer's direction, with an Askania magnetometer adjusted to a sensitivity of 24·0 gammas per scale division. All readings were referred to a base near Glenholme, at the southern end of the traverse.

The magnetic anomalies are shown in Figure 6. Certain general features are worthy of notice. The maximum value of the magnetic anomaly occurs at the same point as the maximum gravity anomaly. Like the gravity profile, the magnetic profile is steeper on the south, in the neighbourhood of the Cobequid fault, than on the flank of the Cumberland Basin to the north. In a general way, therefore, the magnetic anomalies would appear to outline the uplift of the pre-Carboniferous rocks in much the same fashion as the gravity anomalies.

The magnetic anomaly profile to be expected from uniform magnetization by the earth's field is also shown in Figure 6, for comparison with the observed profile. An examination of the two profiles reveals that while there is some tendency for the observed anomaly to approximate the theoretical form near the southern and northern ends of the traverse, the profiles differ markedly in the central portion. The observed profile exhibits a sharp reversal just north of the main maximum, and a second maximum still farther north. These sharp features are not suggested by the calculated profile, and therefore appear to be due to rapid variations in magnetic properties. The magnetic highs most

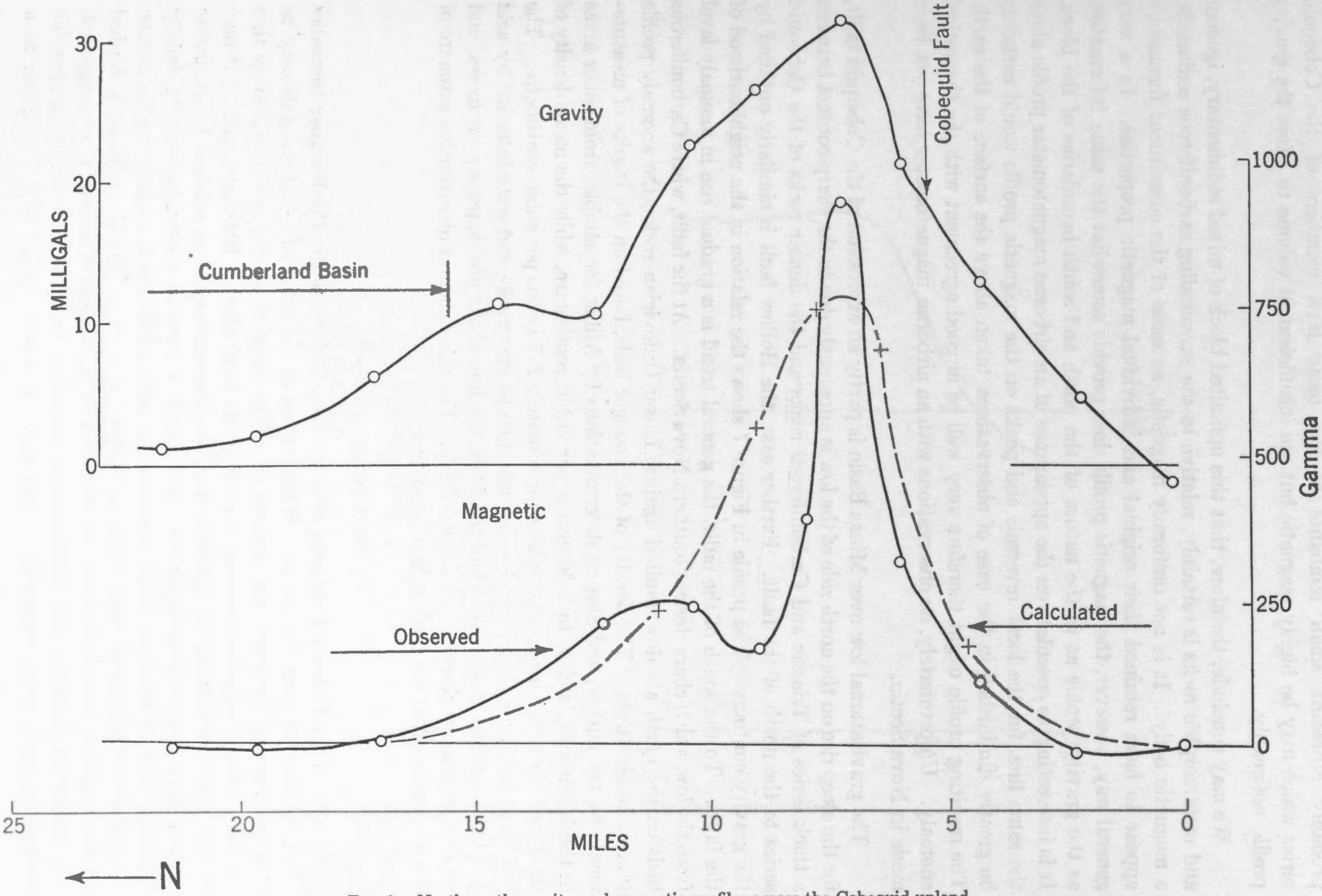


FIG. 6. North-south gravity and magnetic profiles across the Cobequid upland.

probably represent small remnants of the basic lava members of the Cobequid series which may be highly magnetic but are insufficient in volume to affect the gravity profile noticeably.

We may conclude, therefore, that this upfaulted block of mixed sedimentary, igneous and metamorphic rocks is certainly, relative to the surrounding carboniferous sediments, a magnetic body. It is not uniformly magnetic, as some of the constituent formations appear to have retained their original and individual magnetic properties. In a very general way, however, the magnetic profile does provide somewhat the same information as the gravity profile as to the nature of the north and south boundaries of the block. It is interesting to speculate on the appearance of an airborne magnetometer profile along the same line, for the local reversals and peaks on the magnetic profile would certainly be greatly diminished in the case of observations taken above the surface of the earth. The resulting profile might therefore very well be in good agreement with the theoretical anomaly. Unfortunately, no observations with an airborne magnetometer have yet been made in Nova Scotia.

The gravitational low over Minas Basin is partly an expression of the Cobequid fault, for the steep rise on the north side of the low is apparently due to the sharp contact between a thick series of Triassic and Carboniferous rocks and the denser rocks of the Cobequid series to the north of the fault. Farther east, the Hollow fault is similarly outlined by the gravity contours. The profile in Figure 7 shows the relation in the neighbourhood of the fault. To the south of the fault, the general trend is a gradual rise in anomaly level from the low which characterizes southern Nova Scotia. At the fault, where Carboniferous beds on the north are downfaulted against Lower Ordovician rocks, the anomaly profile takes a sudden drop. The density of the younger beds, based on the results of measurements by the author, and also on determinations by Miller for samples from other areas in the Maritimes, is close to 2·50 grams per cubic centimetre, while the mean density of the Lower Ordovician rocks must be approximately 2·7 grams per cubic centimetre. The latter consist of metamorphosed sediments such as greywacke and slate intruded by acid and basic igneous rocks. North of the fault, the line of the profile passes out to sea, and no further gravity observations are available. For this reason a quantitative estimate of the displacement of the fault is hardly possible.

The Cumberland Basin

North of the Cobequid uplands, over the Cumberland Basin, the Bouguer anomalies again decrease to negative values. While values of the order of − 30 milligals may be observed north of Amherst, the analysis of a later chapter (see Figure 18) will show that the most intense negative anomaly is a relatively local effect. Broadly speaking, it may be said that the decrease in anomaly from the pre-Carboniferous uplands to the centre of the basin is from + 15 milligals to − 25 milligals, a decrease of 40 milligals. If a density deficiency of 0·17 gram per cubic centimetre is assumed for the Carboniferous sediments, the indicated thickness of these rocks is 19,000 feet. Shaw (21) has recently published structure sections across the basin, on which about 22,000 feet of sediments are suggested. The agreement between the thicknesses as estimated by gravimetric and stratigraphic methods is quite good, especially as the figure 19,000 feet may be taken rather as a

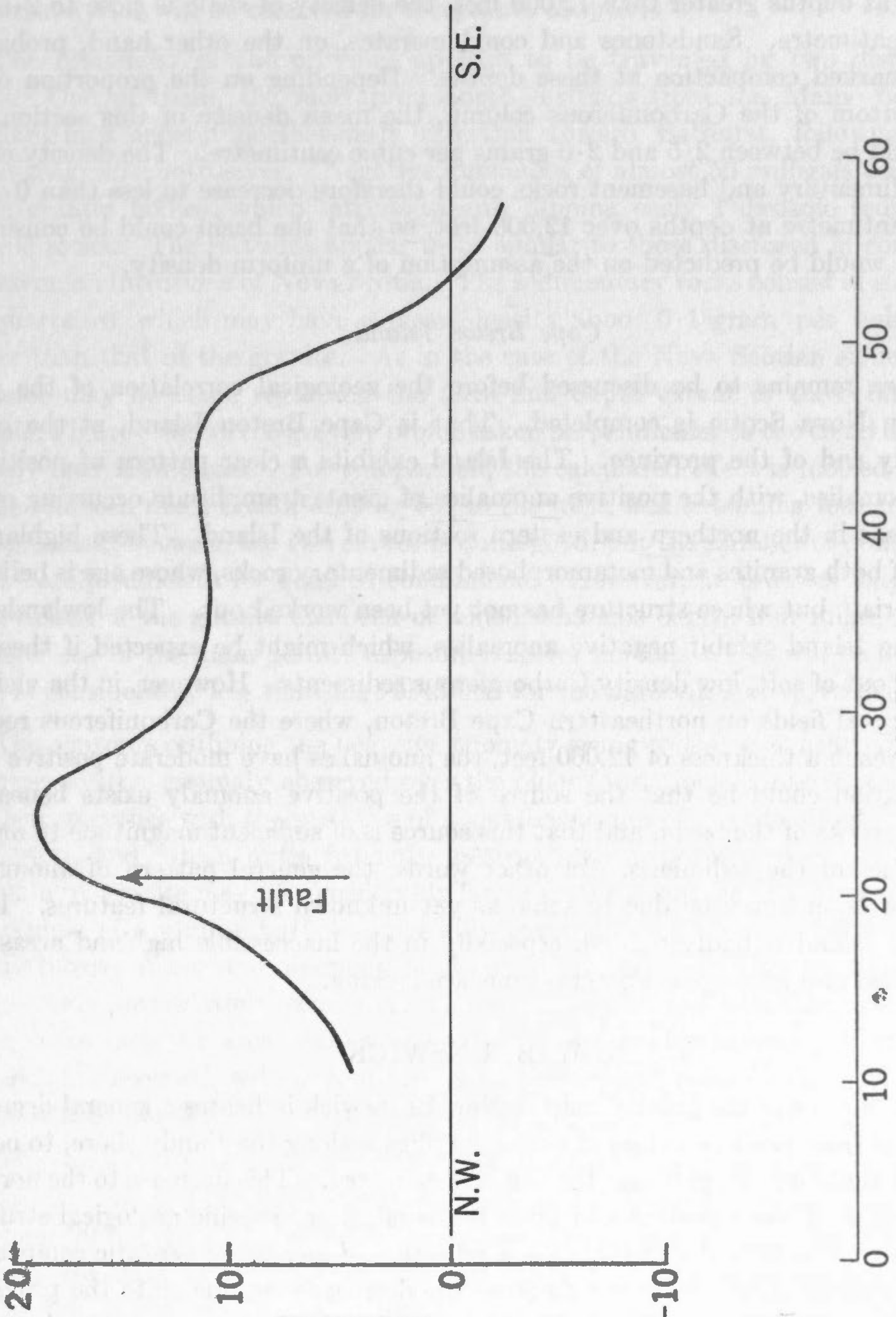


FIG. 7. Gravity profile across the Hollow fault.

minimum value. The sedimentary column contains a considerable proportion of shale, the density of which may be expected to increase with depth, as shown by Hedberg (8). Thus, the density deficiency of the strata may decrease with depth, so that the average value is less than 0·17 gram per cubic centimetre. Roughly speaking, Hedberg's rule shows that, at depths greater than 12,000 feet, the density of shale is close to 2·6 grams per cubic centimetre. Sandstones and conglomerates, on the other hand, probably do not suffer marked compaction at these depths. Depending on the proportion of shale near the bottom of the Carboniferous column, the mean density of this section of the column would be between 2·5 and 2·6 grams per cubic centimetre. The density contrast between sedimentary and basement rocks could therefore decrease to less than 0·1 gram per cubic centimetre at depths over 12,000 feet, so that the basin could be considerably deeper than would be predicted on the assumption of a uniform density.

Cape Breton Island

One area remains to be discussed before the geological correlation of the gravity anomalies in Nova Scotia is completed. That is Cape Breton Island, at the extreme northeasterly end of the province. The Island exhibits a clear pattern of positive and negative anomalies, with the positive anomalies of greatest amplitude occurring over the highland areas in the northern and eastern sections of the Island. These highlands are composed of both granites and metamorphosed sedimentary rocks, whose age is believed to be Precambrian, but whose structure has not yet been worked out. The lowlands in the centre of the Island exhibit negative anomalies, which might be expected if these areas were carved out of soft, low density Carboniferous sediments. However, in the vicinity of the Sydney coal fields on northeastern Cape Breton, where the Carboniferous rocks are believed to reach a thickness of 12,000 feet, the anomalies have moderate positive values. One explanation could be that the source of the positive anomaly exists beneath the sedimentary rocks of the basin, and that this source is of sufficient magnitude to mask the negative effect of the sediments. In other words, the general pattern of anomalies in Cape Breton Island may be due to some as yet unknown structural features. Further work on the Island is badly needed, especially in the inaccessible highland areas where both geological and geophysical observations are lacking.

NEW BRUNSWICK

An examination of the gravity map of New Brunswick indicates a general decrease in anomaly level from positive values of over 20 milligals along the Fundy shore, to negative anomalies of about 40 milligals near the Quebec boundary. This decrease to the northwest is very gentle, and has superimposed upon it the effects of specific geological structures. There appears to be little doubt that it is a reflection of increasing isostatic compensation toward the interior of the continent, because the decrease continues into the province of Quebec, reaching negative values of 60 milligals along the Laurentians uplands north of the St. Lawrence river.

The general isostatic trend is interrupted or distorted in several places by more local, but still major, gravitational effects. Within the generally positive area near the coast variations occur, due apparently to density variations in the pre-Carboniferous rocks which are here exposed at the surface. Farther north, in the region between Sussex and Shediac, the interpretation of effects is complicated by the juxtaposition of deep synclines of Carboniferous formations and buried ridges of pre-Carboniferous rocks. However, this area has been covered with a denser network of stations than the province as a whole, and a discussion of it will be reserved for a separate chapter.

The remainder of the province appears to be traversed by two distinct negative trends. One of these, the most pronounced, extends from the Maine boundary near McAdam in a general northeasterly direction toward Bathurst, following the line of Devonian granite intrusives. Negative anomalies of almost 50 milligals occur over some of the granite bodies, which intrude steeply-dipping early Palæozoic sedimentary and volcanic rocks. The relations appear to be similar to those discussed in connection with the Devonian intrusions of Nova Scotia. The sedimentary rocks consist of slates, argillites and quartzites, which may have a mean density about 0·1 gram per cubic centimetre greater than that of the granite. As in the case of the Nova Scotian structures, certain estimates may be made regarding the form and depth extent of these bodies. As an example, Figure 8 shows the gravity profile taken perpendicular to the trend of the negative anomaly near Hawkshaw. For comparison, the calculated effect is plotted for a body of granite fourteen miles broad, dipping 60° to the west, and extending four miles in depth. The agreement between the two curves is quite good, but the number of points of observation is barely sufficient for detailed comparison. However, an order of magnitude of the depth extent of the granite has been obtained, and this depth, four miles, appears to be characteristic of the main granite exposures farther northeast. It will be noted that this depth is considerably less than that obtained for the batholiths of Nova Scotia.

The contours outlining the negative anomaly swing to the west near Kilburn, so that the more positive anomaly observed over the older formations is interrupted in this area. This fact, together with the presence of a small exposure of granite about four miles west of Kilburn, and fifteen miles from the nearest large exposure, suggests that the areas underlain by granite may be considerably larger than the surface exposures would indicate. An example of a granite batholith partially covered by Carboniferous sediments is seen near Bathurst. A negative anomaly of almost 30 milligals appears to coincide with the granite body immediately southwest of the town, but the anomaly extends for some fifteen miles into the area blanketed by Carboniferous formations. A crescent-shaped batholith is suggested, with a depth extent of some eight miles being required to explain the gravitational effect.

The second of the two major negative trends mentioned above extends from Fredericton, through Chipman to East Galloway. Anomaly values along this feature are about 20 milligals less than to either side. The surface rocks along the course of this anomaly are almost entirely Pennsylvanian beds, but there is strong evidence that the gravity low does not indicate a thickening of these light formations. An anomaly of 20 milligals would be caused by a thickening of the order of 8,000 feet, but in the Chipman area, near the axis of the anomaly, pre-Carboniferous formations are exposed in a small area along Coal Creek. A few miles to the west, near Minto, bore holes show that the Carboniferous formations are only a few hundred feet thick (Geol. Surv. Canada, Maps 1003 A and 1004 A, Minto and Chipman sheets, 1951). The negative anomaly appears

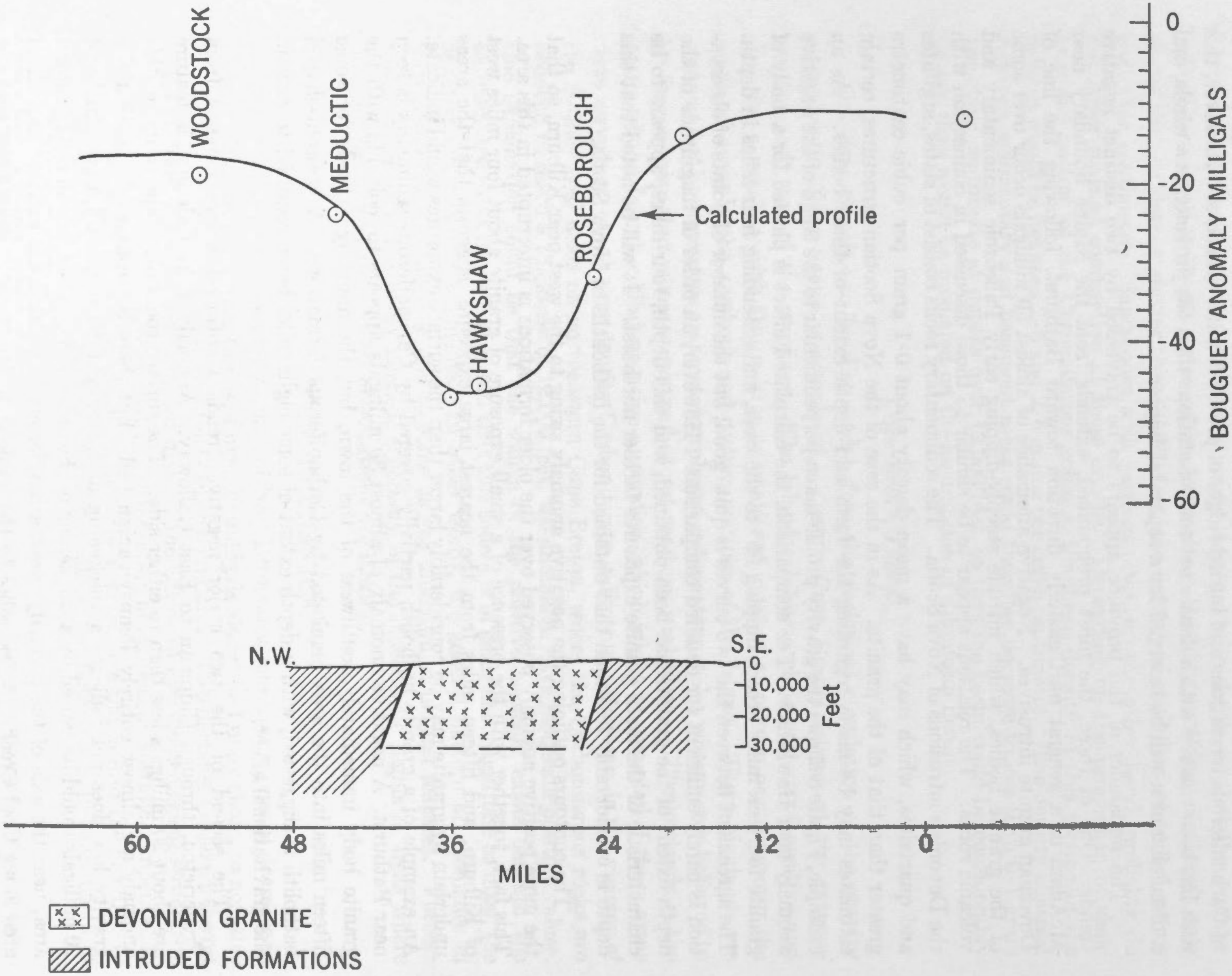


FIG. 8. Calculated and observed gravity profiles through Hawkshaw, N.B.

therefore to be caused entirely by density variations within the pre-Carboniferous basement. It may indicate a second line of Devonian granites similar to the McAdam-Bathurst group.

The two negative features which have been described are separated by a prominent positive anomaly which may be traced from near Shippegan through Newcastle almost to Doaktown. Presumably this indicates an area of denser pre-Carboniferous basement, which could in turn indicate an absence of Devonian granite intrusions. There are, of course, density variations in the intruded rocks themselves, as they range from sedimentary to volcanic formations. Certain quite local highs, such as that at Upper Blackville, are probably due to belts of the denser volcanics within the early Palæozoic group. Over most of central and northern New Brunswick, however, the station density is not sufficient to trace these smaller features. The problem of analysing local anomalies over the Carboniferous basin of the southeastern portion of the province will be treated in the next section.

ANALYSIS OF LOCAL ANOMALIES IN SOUTHEASTERN NEW BRUNSWICK

A. H. MILLER AND G. D. GARLAND

The accompanying map (Fig. 9) shows gravimeter stations and Bouguer anomaly contours over an area extending from the Nova Scotia boundary westward to Chipman, and from Point Wolfe northward to Buctouche. In the southern portion of this area, pre-Carboniferous rocks consisting largely of a series of lavas intruded by granite and diorite are exposed along the Caledonian Mountains, paralleling the Bay of Fundy shore. North of the mountains, Mississippian rocks lie in major synclines, separated by other pre-Carboniferous ridges. Many of these relationships, however, are concealed by a blanket of relatively undisturbed Pennsylvania strata, which covers practically the entire northern half of the area. As the Mississippian series contains two formations of commercial interest, the possibility of tracing its distribution beneath the Pennsylvanian cover is of some importance. Oil and gas are produced from sandstones of the Albert formation in which salt and bituminous and oil shales also occur. The Albert formation occurs in the lower part of the Mississippian, overlying the lowest formation, the Memramcook. It is overlain by the Moncton group of sandstone, shale and conglomerate, which in turn is overlain by the Windsor group. The Windsor group carries important quantities of gypsum and salt.

The tracing of buried pre-Carboniferous ridges in the Moncton area by gravitational methods was first undertaken by the Dominion Observatory, in co-operation with the Geological Survey, in 1935 (13). Gravitational highs, as indicated by the torsion balance, were observed over the ridge which passes south of Moncton, crossing the Petitcodiac River between Moncton and Lower Coverdale. By means of gravimeter observations, Miller (14) later indicated the eastward extension of this ridge, and of the Lutz Mountain ridge north of Moncton, toward the coast of Northumberland Strait. It is the purpose of the present chapter to study the westward trend of these structures, utilizing data which has been obtained more recently.

In addition to the gravimeter values, use will be made of torsion balance and magnetometer observations obtained during 1943, and previously unpublished. This work was under the direction of A. H. Miller, assisted in the field by T. E. R. Mitton and Donald H. Gorman, who were at that time undergraduates of the University of New Brunswick. Seventy-seven stations were established with two torsion balances, although a photographically recording instrument was used for most of the work. The torsion balance gradients, corrected for topography to a distance of 60 metres from the instrument, are plotted on the gravity contour map. For a number of stations the terrain correction is rather large (the maximum value is about 70 Eotvos units as compared to a maximum anomaly of 100 Eotvos units), so that for these stations there is some uncertainty in the final values, due to variation in the density and depth of soil. The results provided by this survey indicated the presence of several of the main gravitational trends of the area,

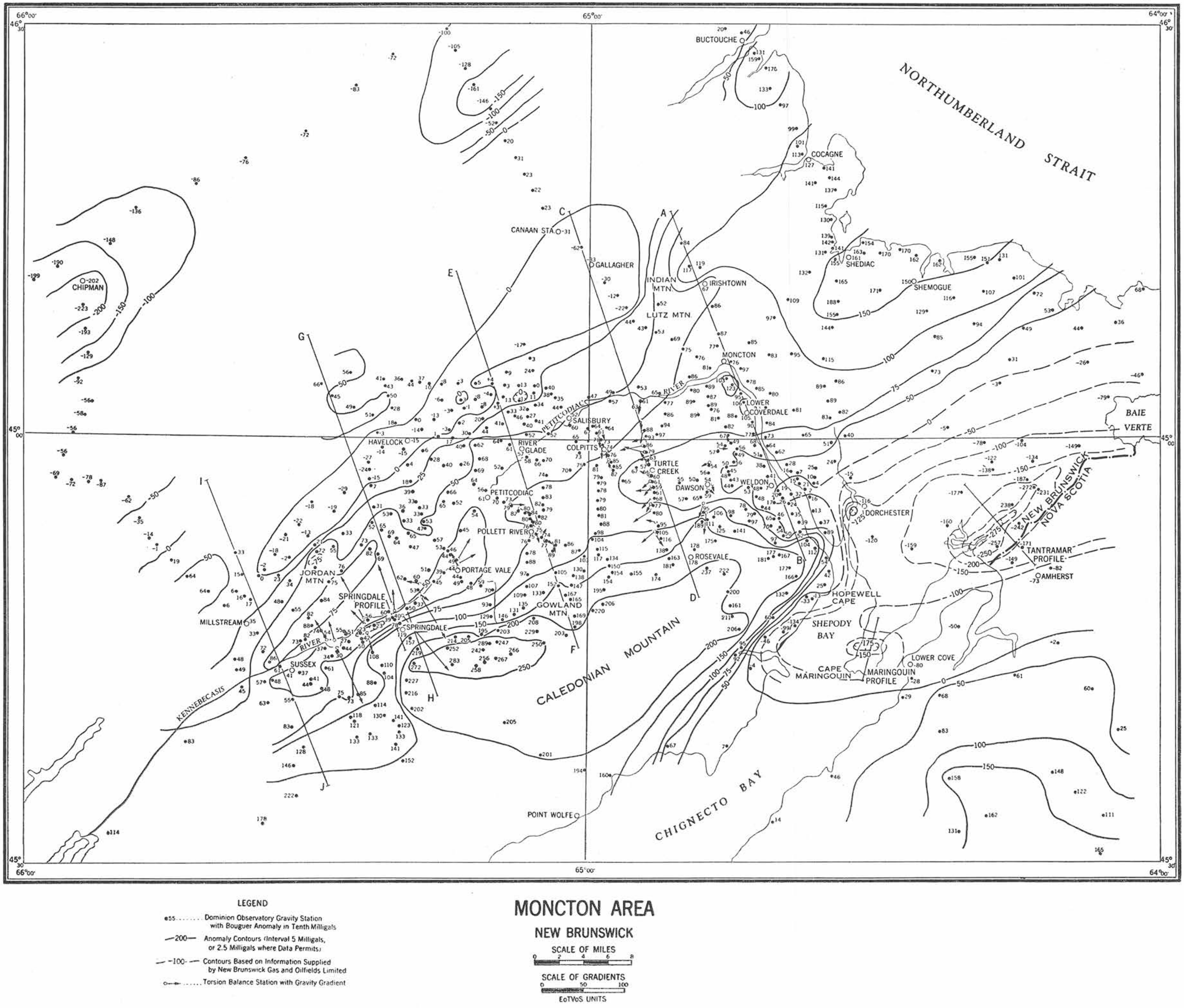


Fig. 9. Gravity anomaly map of the Moncton area.

notably the high extending westerly from the vicinity of Lower Coverdale (Fig. 10) and the prominent low near Springdale. However, as these effects have now been more thoroughly outlined by gravimeter observations, a separate discussion of the torsion balance results will not be given, but all the information will be considered together.

The contour map shows a prominent positive anomaly over the exposed pre-Carboniferous rocks of the Caledonia Mountain. This anomaly stops rather abruptly at the Petitcodiac River, but a parallel positive trend farther to the north extends from near Indian Mountain to the Northumberland coast and apparently crosses Prince Edward Island. To the northwest, the positive values decrease rapidly, from the maximum of about 20 milligals over the Caledonian Mountain, to negative anomalies of the same magnitude near Chipman in the northwest corner of the area. This gradient is largely a reflection of the major negative trend which passes through the latter town, and was described in the previous chapter. It will be recalled that the negative anomaly was there attributed to a density deficiency in the pre-Carboniferous basement, and not to the Carboniferous formations themselves. The effect of basement density variations may be seen also by noting the anomaly values over exposed pre-Carboniferous rocks in different parts of the area. Thus, over the Caledonia Mountain area, the values range from 160 to 280 in units of one-tenth milligal. The lower values are observed over the granitic rocks of the complex, while the highest anomalies occur over the basic lavas. Fourteen miles to the northwest, at Jordan Mountain, the anomaly immediately over exposed basement rocks is 75 units. Twenty miles from the Caledonia Mountain, near Havelock, the anomaly over pre-Carboniferous areas is about 60 units. There is thus a pronounced anomaly gradient which must be taken into account in any analysis of the more local effects.

The accompanying table (Table 2*) shows measured densities of rock samples from a number of formations from the area under consideration. It is apparent that there are considerable variations within any one formation, but on the whole the pre-Carboniferous rocks are more dense. Local gravity anomalies may therefore be expected due to there causes: density variations within the Carboniferous beds, variations in the thickness of the strata, or density variations in the pre-Carboniferous rocks. For the purpose of studying variations in the thickness of the Carboniferous beds, an average density of 2·5 for the sedimentary rocks and 2·67 for the pre-Carboniferous rocks is probably a reasonable choice. This gives a density contrast of 0·17 gram per cubic centimetre, so that over a broad basin, where the simple Bouguer formula may be applied, a thickness of 470 feet of strata produces a negative anomaly of one milligal. However, it must be emphasized that in many cases the three effects noted above cannot be distinguished with certainty.

The general features of the area will be studied first on five parallel profiles, whose position is shown on the map. The most easterly profile (AB) extends along the Petitcodiac River from near Hopewell Cape to Moncton, then along the same line to near Indian Mountain. The anomalies along this line have been discussed by Miller (14), but the establishment of a number of new stations permits greater detail to be shown. The regional gradient appears as a fairly gentle slope on this particular profile, so that local features stand out well. A high between Lower Coverdale and Moncton indicates the

---

* This table was compiled for the Dominion Observatory some years ago by the late Dr. J. A. L. Henderson of the New Brunswick Gas and Oilfields Ltd.

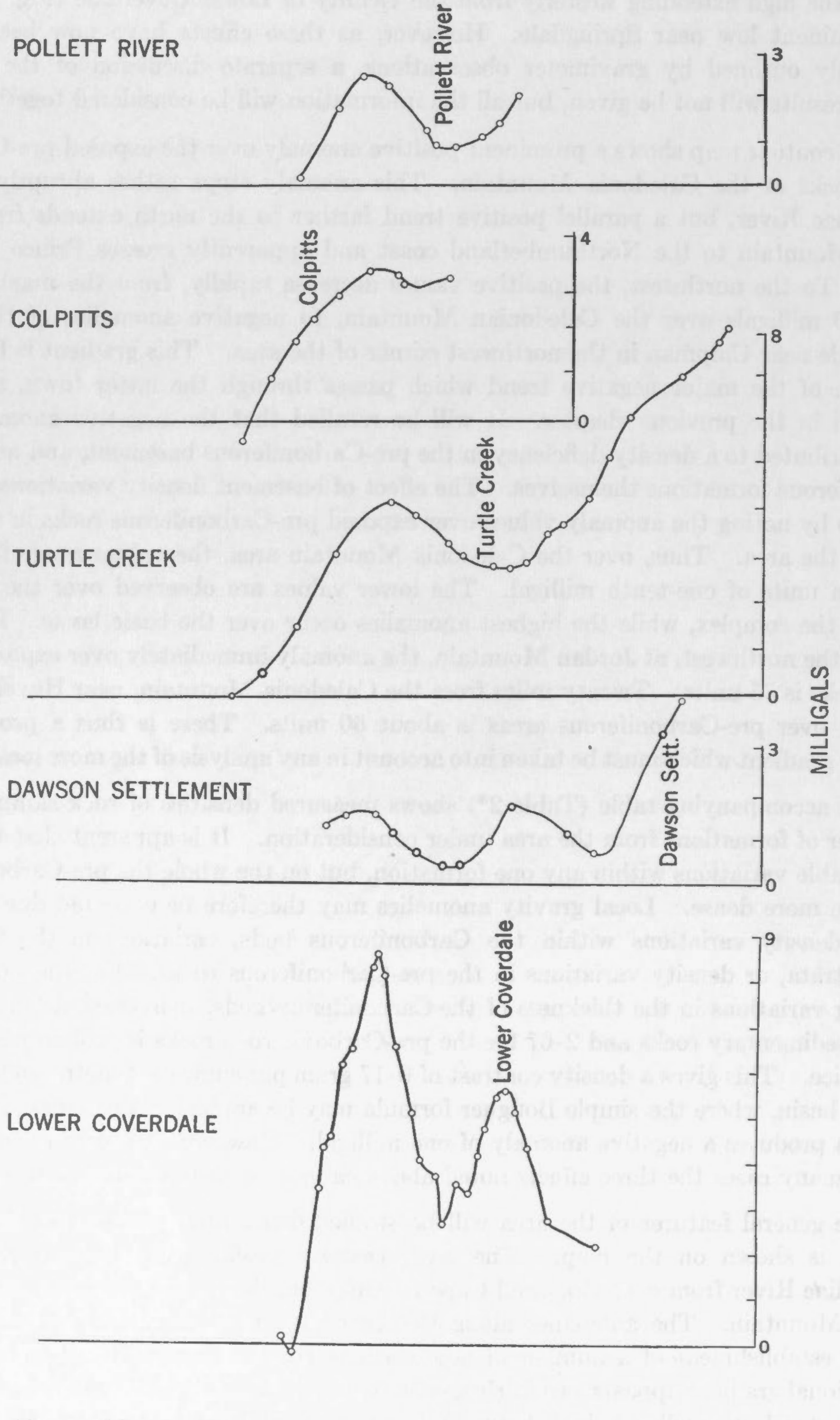


Fig. 10. Gravity profiles observed with the torsion balance.

pre-Carboniferous ridge which separates major Mississippian basins to the north and south. This ridge is covered by only about 350 feet of Pennsylvanian sediments, so the high associated with it rises almost to the regional curve. The basin to the south, between the ridge and the Caledonia Mountain, produces a mean anomaly of about 10 milligals

TABLE 2.

Densities of Rocks of the Moncton Area Measured and Compiled by Dr. J. A. L. Henderson of the New Brunswick Gas and Oilfields Ltd.

Classification of Rock by Dr. J. A. L. Henderson	Probable Geological Survey Classification	Nature of Rock	Samples Tested	Range in Density	Average Density
				gm/cc.	gm/cc.
Permian to Middle Carboniferous	Pennsylvanian	Conglomerate	10	2·34 — 2·72	2·42
		Sandstone	20	2·11 — 2·46	2·32
		Limestone	4	2·63 — 2·70	2·66
Lower Carboniferous Red Beds	Mississippian	Conglomerate	10	2·46 — 2·57	2·53
		Sandstone	19	2·34 — 2·62	2·49
		Shale, Marl, Clay	12	2·16 — 2·61	2·39
		Limestone	2	2·59 — 2·68	2·64
		Ash	3	2·32 — 2·38	2·36
		Gypsum Rock	1	—	2·28
		Clay Ironstone	1	—	2·52
Albert Shales	Mississippian (Albert Formation)	Sandstone (brown Petroliferous)	3	2·24 — 2·32	2·29
		Sandstone (calcareous)	11	2·45 — 2·65	2·55
		Shale (bituminous)	13	1·59 — 2·21	1·89
		Shale (calcareous)	12	2·29 — 2·63	2·46
		Limestone	3	2·50 — 2·73	2·65
Lower Carboniferous	Mississippian	Conglomerate	4	2·55 — 2·66	2·61
		Sandstone	25	2·42 — 2·74	2·58
		Arkose	8	2·50 — 2·65	2·60
		Shale	9	2·43 — 2·77	2·67
Pre-Carboniferous (Devonian?)	Pre-Carboniferous	Granite	3	2·57 — 2·65	2·61
		Sandstone	2	2·57 — 2·66	2·62
		Sandstone (black)	1	—	2·44
		Shale (carbonaceous)	1	—	2·71
		Limestone	1	—	2·64
		Arkose	1	—	2·70
Pre-Carboniferous (Silurian-Cambrian)	Pre-Carboniferous	Shale (carbonaceous)	1	—	1·57
		(Graptolite?)	1	—	2·49
		Not stated	2	2·63 — 2·71	2·67
Pre-Carboniferous (Precambrian?)	Pre-Carboniferous	Shale (carbonaceous)	1	—	2·48
		Gneiss, Conglomerate, Sandstone slate, Schist	10	2·62 — 2·97	2·75
Pre-Carboniferous (Precambrian)	Pre-Carboniferous	Limestone, Schist, Trachyte, Quartzite, Gneiss	12	2·61 — 2·79	2·70
	Pre-Carboniferous	Granite, Schist	7	2·59 — 2·96	2·77

below the regional. This would be equivalent to a maximum thickness of about five thousand feet of sediments. The increase in thickness southward from the ridge appears to be quite rapid at first, then more gradual toward the centre of the basin. Superimposed upon the basin effect near Weldon is a sharp local negative anomaly of 5 milligals. This has been discussed by Miller (14), who related it to the Weldon salt deposit, a lens of salt about 1,500 feet thick occurring in the Albert formation. The northerly basin, between Moncton and the pre-Carboniferous ridge near Irishtown, appears to be only about half as deep as the southerly basin, or about 2,500 feet. Both sides of the basin appear to be steep-sided, judging from the rapid decrease in anomaly over the edges. In fact, there is some suggestion from the profile that the basin is deepest near the edges. There is evidence of faulting along Indian Mountain near Irishtown (Geol. Surv. Canada, Map 646A, Moncton Sheet, 1941) which may explain the steep contact between ridge and basin.

The second profile (CD) is taken about nine miles west of the first. It follows a line from near Rosevale, through Turtle Creek to Gallagher. On this profile the two ridges described above appear more as a single structure, separated by only a moderate thickening of sediments. The southerly edge of the south ridge is indicated clearly by both the torsion balance and gravimeter observations. Because of the uncertainty of the regional curve, it is hardly possible to estimate the exact thickness of the sedimentary cover over the pre-Carboniferous uplift, although the presence of the rather sharp magnetic anomalies north of Turtle Creek station suggest it is not great. The basin to the south is still prominent, but its depth is apparently less than that computed for the first profile. North of the most northerly ridge a third basin is suggested, with a depth of some five thousand feet. The negative anomaly associated with this basin is a prominent feature of the gravity map, as it extends southwest through Havelock toward Millstream, a distance of forty miles. On the north side of the basin the values increase again, indicating the basin edge to be near Canaan Station. This is in accordance with drilling evidence, as a well drilled near the latter place indicated about 1,100 feet of Pennsylvanian sediments resting directly on pre-Carboniferous granite (Geol. Surv. Canada, Map 604A, Salisbury Sheet, 1941).

The same general relationships are apparent eleven miles farther west on the third profile of the series (EF), which passes from Gowland Mountain on the south, through Pollett River and River Glade, to a point northwest of Salisbury. The relatively high values near the centre of the profile again suggest the continuation of the two ridges of pre-Carboniferous rocks, separated by a shallow basin. To the south of these ridges, a relative low of about 3 milligals suggests a basin with about 1,400 feet of strata, extending from the neighbourhood of Pollett River to the pre-Carboniferous rocks of Gowland Mountain. The northerly edge of the north ridge coincides with a major fault which crosses the Salisbury map-area, and which brings Albert strata to the surface along its south side. To the north of this fault, the sudden decrease in anomaly indicates the thickening of Carboniferous sediments in the most northerly basin. Immediately west of the line of this profile the conditions appear to change. An examination of the contour map indicates that the high near Pollett River, which is associated with the southern ridge, ends abruptly within a few miles of that point, and that its position is taken farther west by a prominent low. The suggestion is therefore that the southern ridge is somehow cut

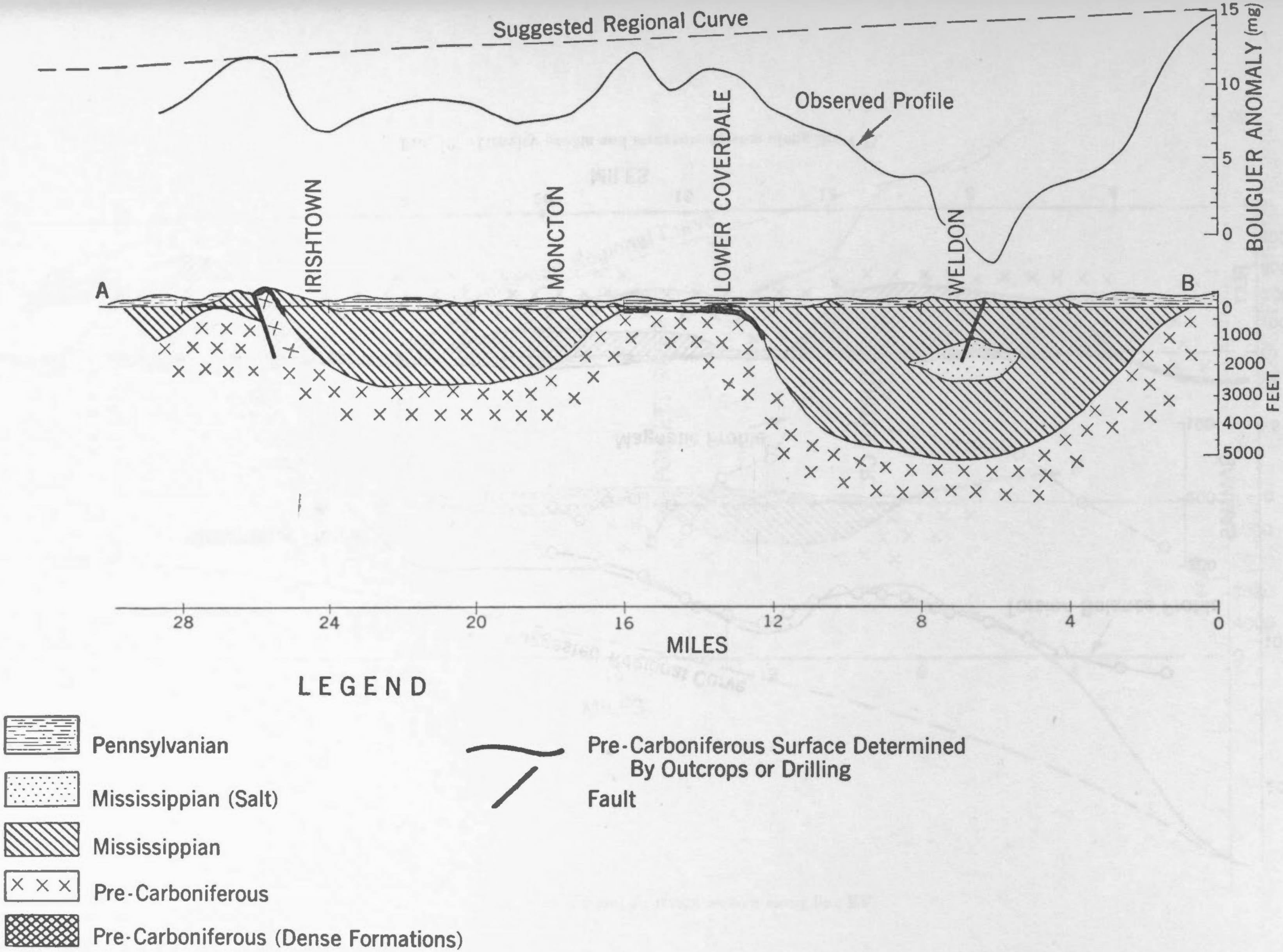


FIG. 11. Gravity profile and structure section along line AB. For this and the following four illustrations the surface geology has been taken from published maps of the Geological Survey, but the depth of the pre-Carboniferous surface, except where it is shown by the heavy line, is inferred from the gravity anomalies.

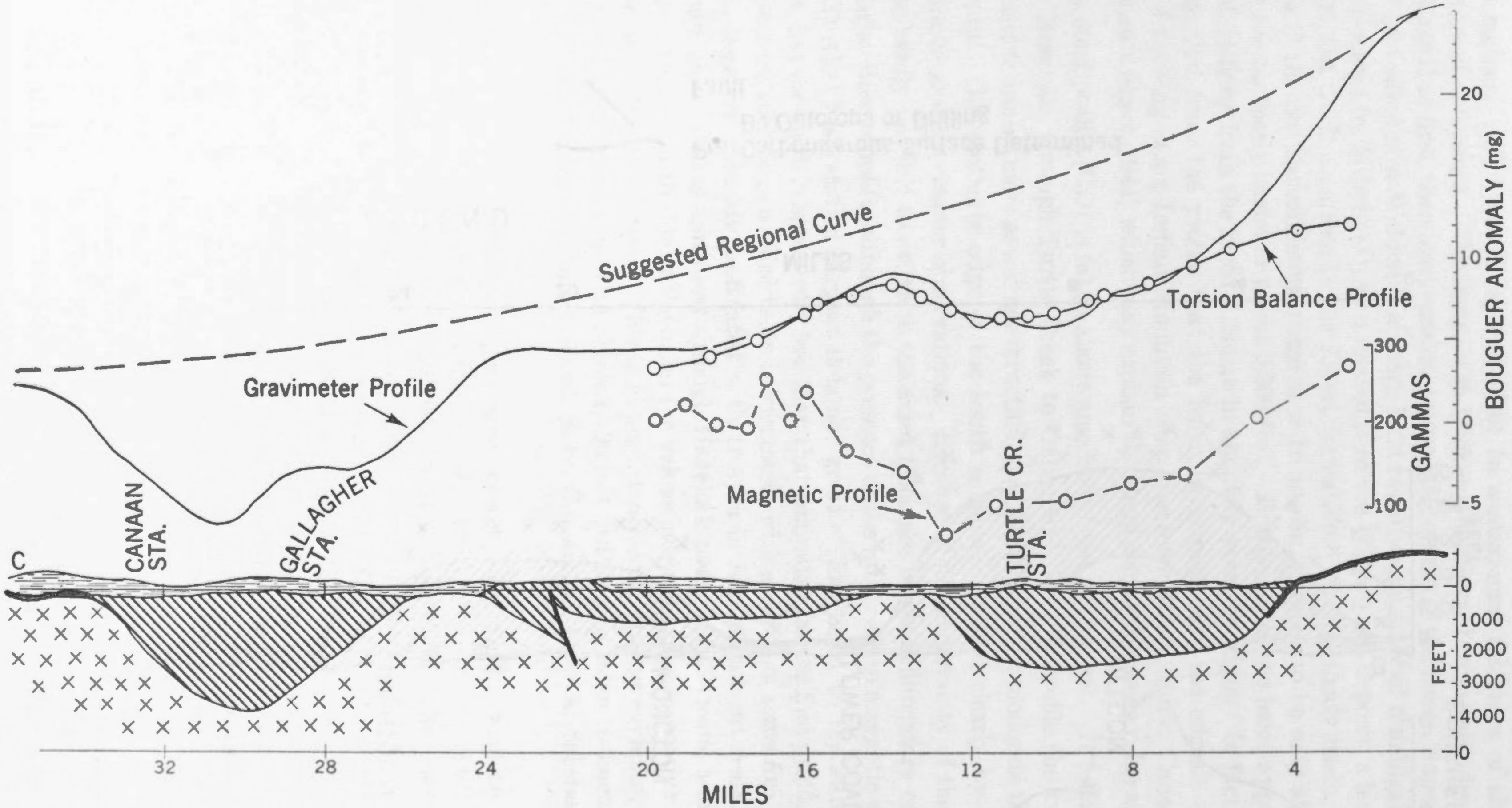


FIG. 12. Gravity profile and structure section along line CD.

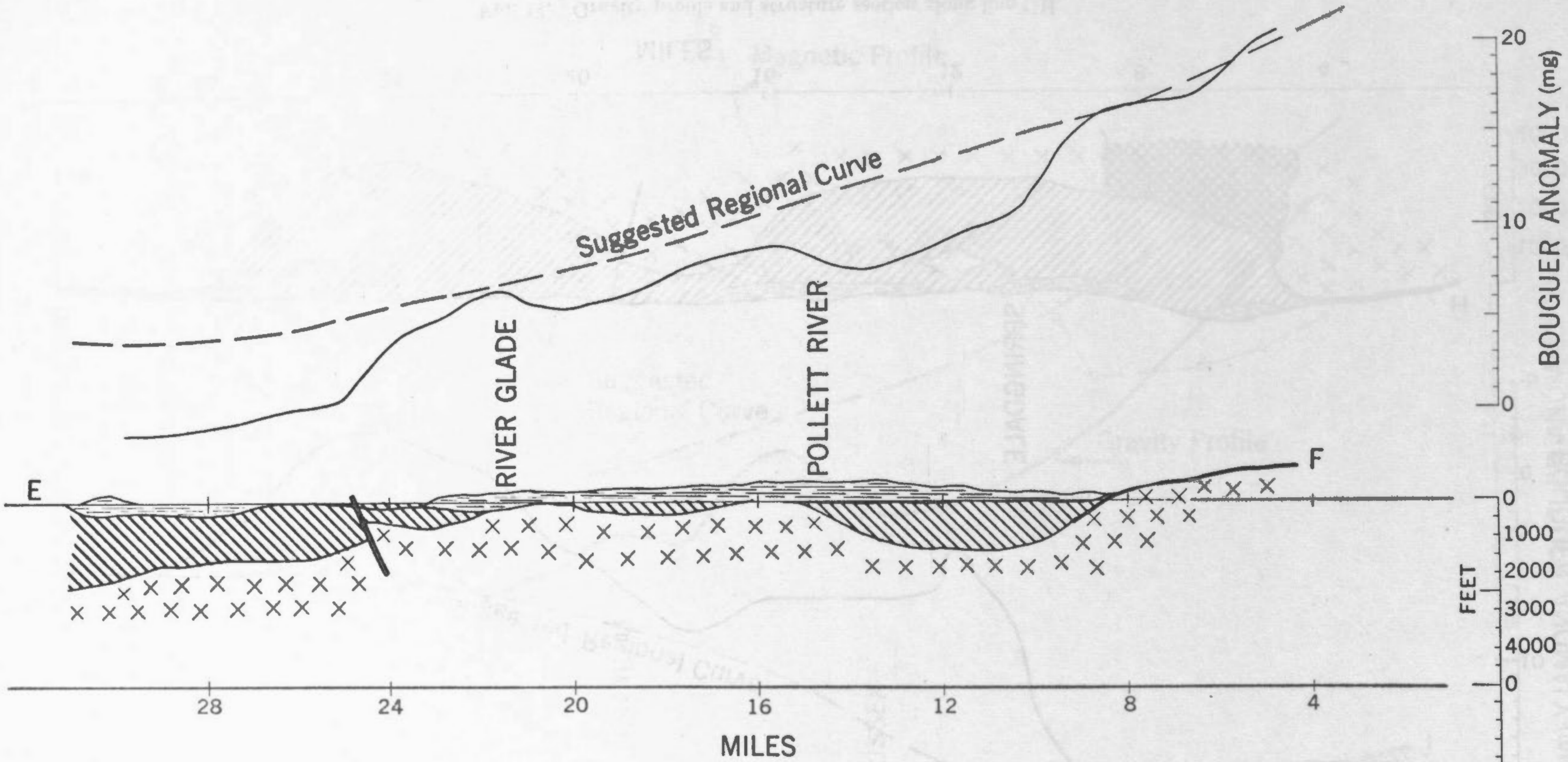


FIG. 13. Gravity profile and structure section along line EF.

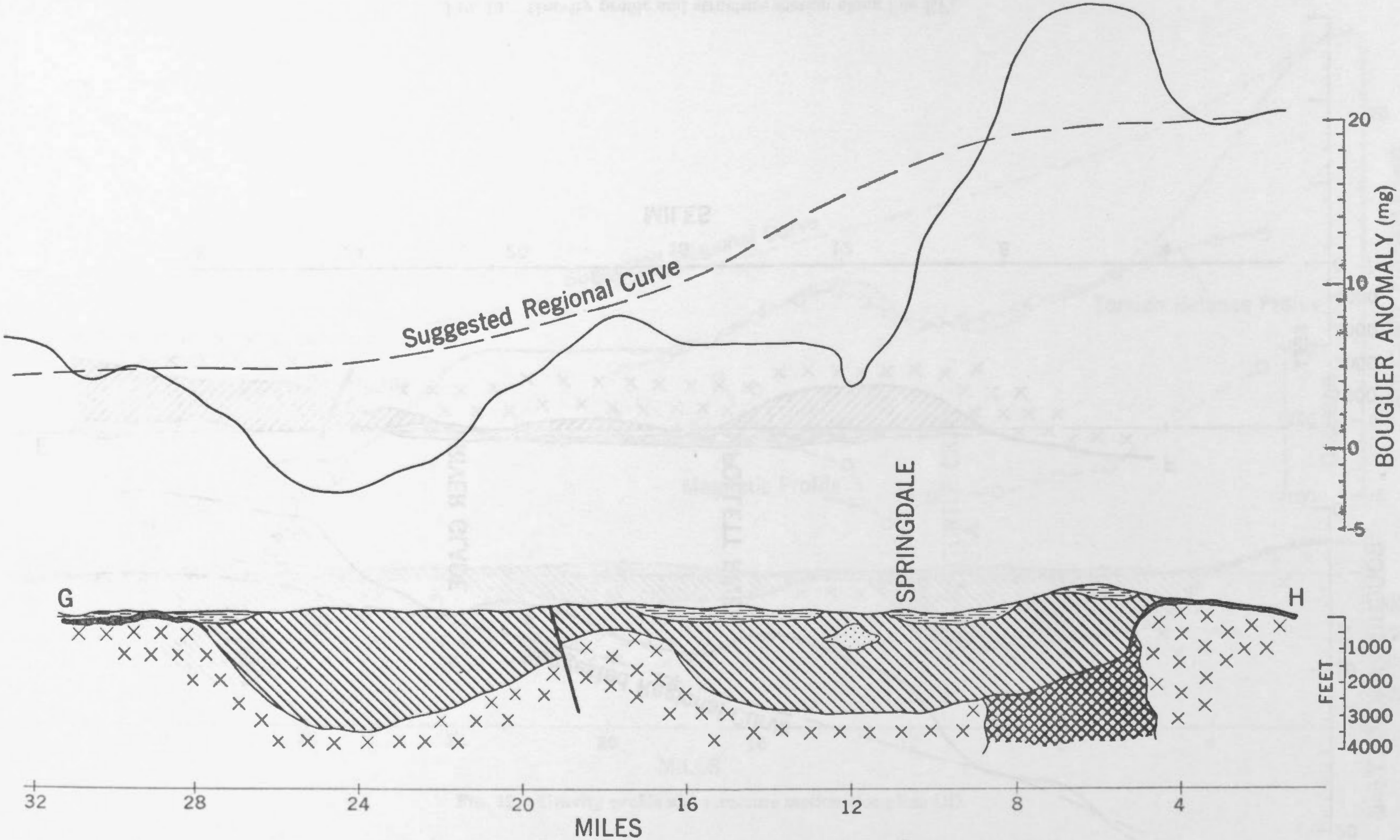


FIG. 14. Gravity profile and structure section along line GH.

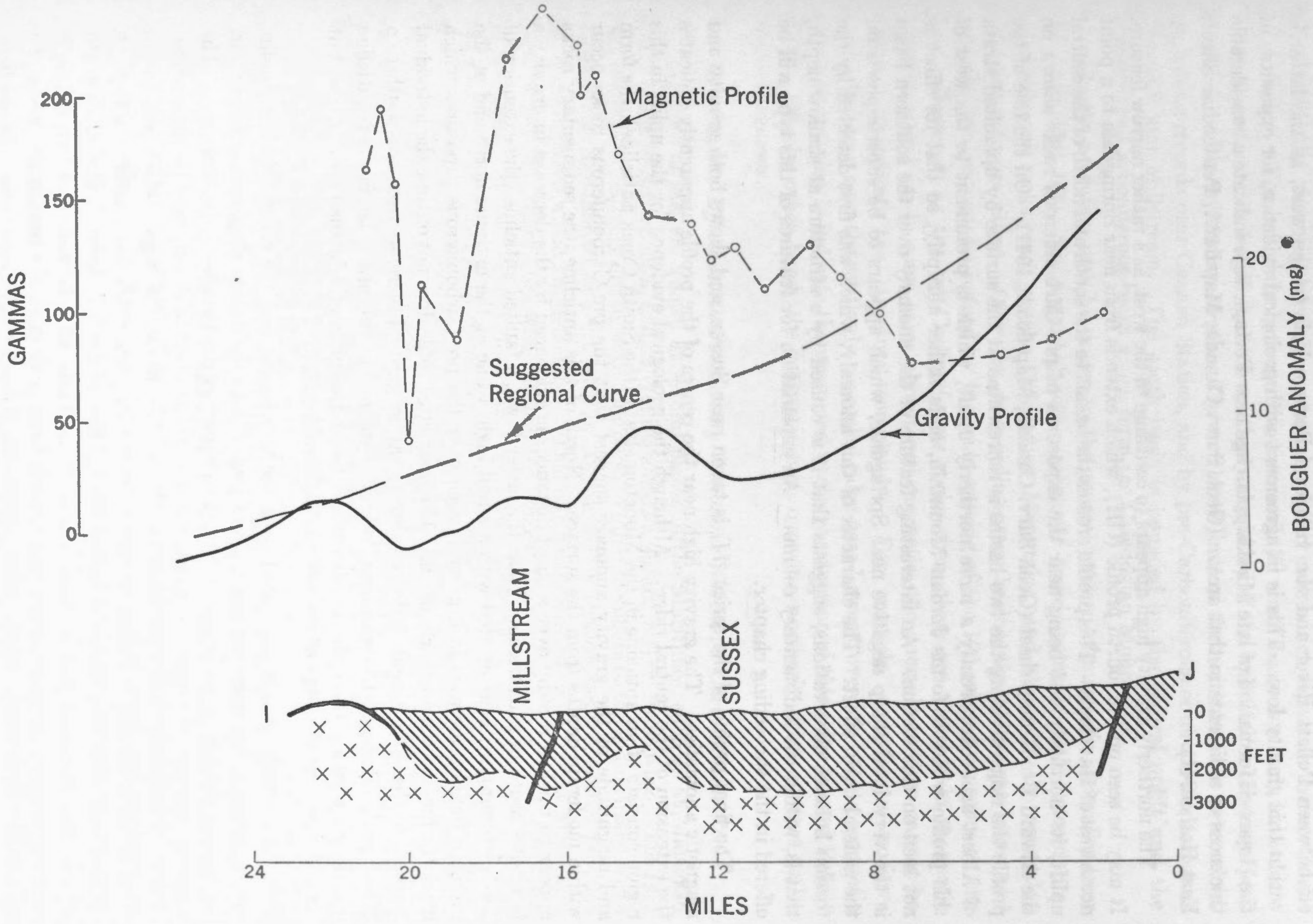


FIG. 15. Gravity profile and structure section along line IJ.

off between Pollett River and the village of Portage Vale to the west, as the latter is within this gravity low. This is in agreement with geological evidence, for exposures of the Hopewell formation of late Mississippian age near Portage Vale indicate a considerable thickness of sediments in that area. (Geol. Surv. Canada, Map 642A, Petitcodiac Sheet, East Half, 1941).

The northerly gravity high appears to continue to the west, as a rather narrow feature. It may be seen on the fourth profile (GH), which extends from near Springdale to a point northwest of Havelock. This profile crosses the basins to the south and north of the central uplift, its northerly end being near the exposures of pre-Carboniferous rocks shown on the Alward Brook map sheet (Geol. Surv. Canada, Map 605A, 1941). On the line of the profile the ridge dividing the two basins is represented at the surface by upfaulted strata of Albert age. Apparently a more northerly uplift, which is prominent to the west of this profile where it forms Jordan Mountain, ends rather abruptly, so that its effect is not seen on this section. An interesting feature of the anomaly over the southern basin is the very local sharp negative near Springdale, which appears to be superimposed on the general basin effect. The character of this anomaly, which was first detected by the torsion balance observations, suggests that it is caused by a structure at shallow depth, that is, within the sedimentary column. An explanation for features of this type will be offered in the succeeding chapter.

The final profile of the series (IJ) is taken near Sussex, and shows both gravity and magnetic anomalies. The gravity high near the centre of the profile apparently indicates the extension of the central ridge. Although the geological evidence for the uplift in this region consists of an anticline in the Moncton strata (the Smith Creek anticline), the form and magnitude of the gravity anomaly suggest that the pre-Carboniferous rocks occur within moderate depths from the surface. North of this anticline, the sedimentary rocks appear to thicken rapidly over a short distance, as evidenced by the decrease in gravity a few miles south of Millstream. Near the latter town, a faulted anticline (the extension of Jordan Mountain) is associated with a small high, while at the extreme north end of the profile a definite increase in gravity is seen over the pre-Carboniferous exposures which mark the limit of the northerly basin. The magnetic profile does not outline the individual features to the same extent, but does show a rather gradual increase from the south to a broad peak of about 150 gammas, reaching its maximum near the faulted anticline mentioned above. Over the northernmost basin the magnetic intensity decreases, but rises abruptly at the edge of the pre-Carboniferous rocks.

The anomaly trends associated with the two basins and the central dividing uplift can be traced a few miles beyond the last profile, into the Sussex map-area. Thereafter, the station density is no longer sufficient to show up the details of the structure. The suggested pattern of ridges and basins, in the area studied in detail, may be summarized briefly. Proceeding westward from the Petitcodiac River, the ridges which are known south of Moncton and at Indian Mountain persist for some miles, but converge to form an uplifted zone with deep basins on either side. These basins may attain a maximum depth of over five thousand feet of light strata. The basin area between the two ridges is probably nowhere as deep as this, and appears to become shallower toward the west. To the west of Pollett River, that is, about twenty-five miles from the Petitcodiac, the southern ridge terminates abruptly, leaving a narrower uplifted zone which separates the north and south basins. The boundary between this zone and the north basin is a fault for at least a major portion of its length, but the southerly boundary of the uplift is for the most part obscured by Pennsylvanian strata. The northerly limit of the north basin is determined by drilling records near Canaan Station, and by pre-Carboniferous outcrops northwest of Havelock and Millstream. The south basin is bounded by the central uplift and the exposed pre-Carboniferous rocks which form the Caledonian Mountains.

Finally, attention may be drawn to the general pattern of magnetic anomalies over the area (Fig. 16*). In general, positive magnetic trends coincide with exposed pre-Carboniferous rocks, such as the Caledonian Mountains, and also with the concealed pre-Carboniferous ridges. Over the deep sedimentary basins, the values are lower and very uniform, as may be judged by the wide spacing of the 100-gamma contours on the map. However, as the pre-Carboniferous rocks themselves are variable in magnetic properties, and are in some cases almost non-magnetic, the anomaly pattern cannot be assumed to indicate the structure completely. For example, conspicuous positive anomalies occur over the southerly concealed ridge near Lower Coverdale but the magnetic map does not clearly indicate the presumed westerly extension of this ridge toward Pollett River. On the other hand, the magnetic high over the northerly ridge appears to be quite continuous.

Gravitational Effects Related to Density Variations Within the Carboniferous Rocks

Deposits of salt are known at several places in the Maritimes, such as at Malagash and Nappan in Nova Scotia, and at Weldon and Dorchester in New Brunswick. The fact that salt has a relatively low density compared to other members of the sedimentary series suggests that accumulations of it, at least at reasonably shallow depths, should produce gravity anomalies which are detectable. This was demonstrated to be true at Malagash, Nova Scotia, by Miller (13), who outlined the deposit there by means of torsion balance observations. Miller's density determinations give a mean value of 2·16 grams per cubic centimetre for salt, and 2·18 grams per cubic centimetre for impure salt. While some of the enclosing rocks exhibited densities of the same order, the mean density of the surroundings was found to be closer to 2·5. The Malagash salt is of Windsor age, and is concentrated along the axis of a major anticline. Miller observed a negative anomaly of about 3 milligals over the deposit, which has a maximum thickness of some three hundred feet.

Near Weldon, a lens-like body of salt is known from drilling records to occur near the top of the Albert formation. Miller (14) has also described the gravitational effect of this body, which may be observed on the first profile of the previous section. This lens, about 1,500 feet thick, occurs at a depth of about 1,300 feet. Miller has shown that the observed gravitational effect is in agreement with that estimated from these dimensions.

An interesting salt formation was encountered near Dorchester during drilling by the Shell Oil Company. The salt evidently is in the form of a typical dome, and produces the sharp circular negative anomaly of about 5 milligals, which may be seen on the map immediately southwest of the town.

---

* The magnetic contours are based on information supplied to the Dominion Observatory through the kindness of the late Dr. J. A. L. Henderson of the New Brunswick Gas and Oilfields Limited. Magnetometer stations were spaced, on the average, at intervals of 500 feet along all traverses shown on the map.

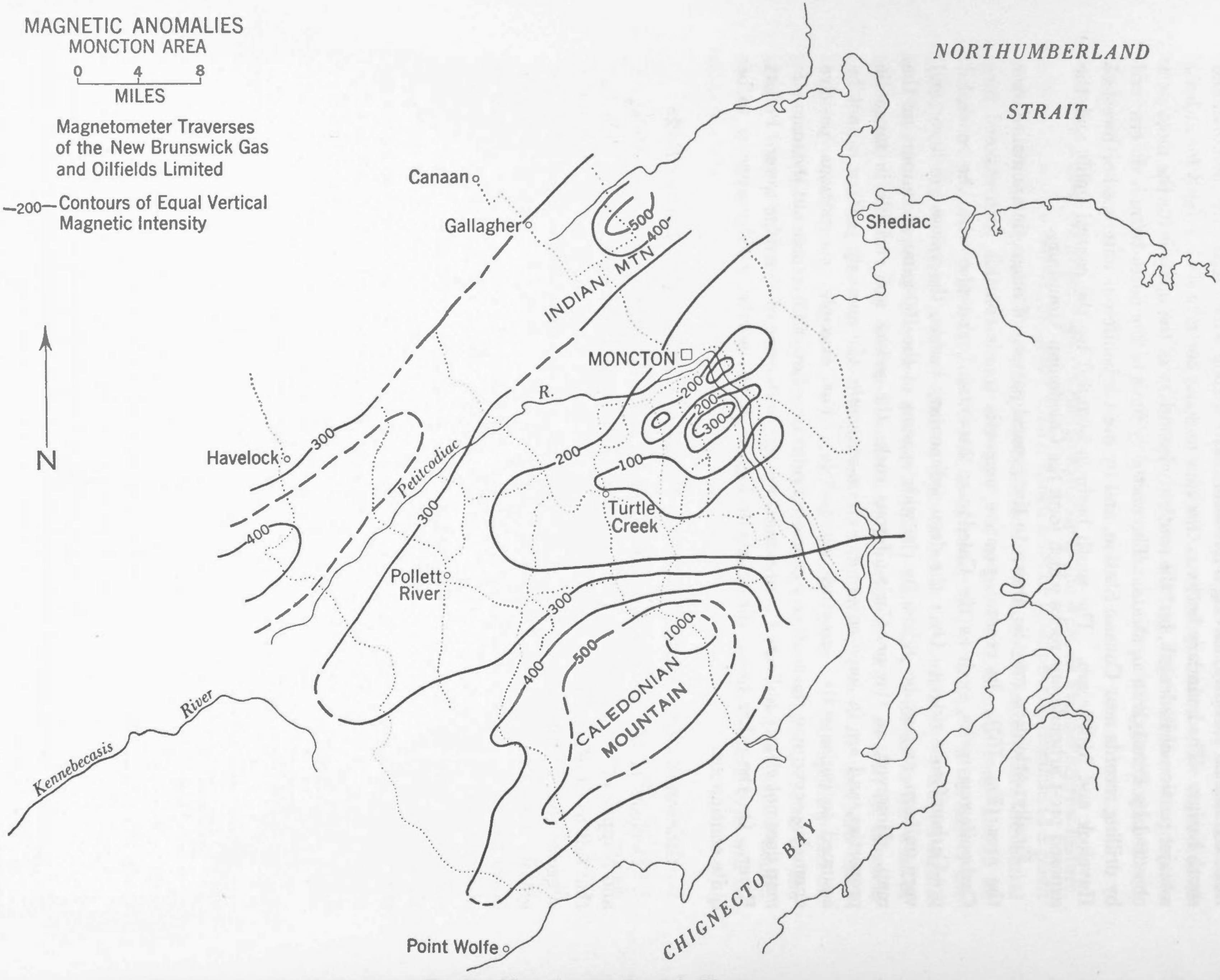
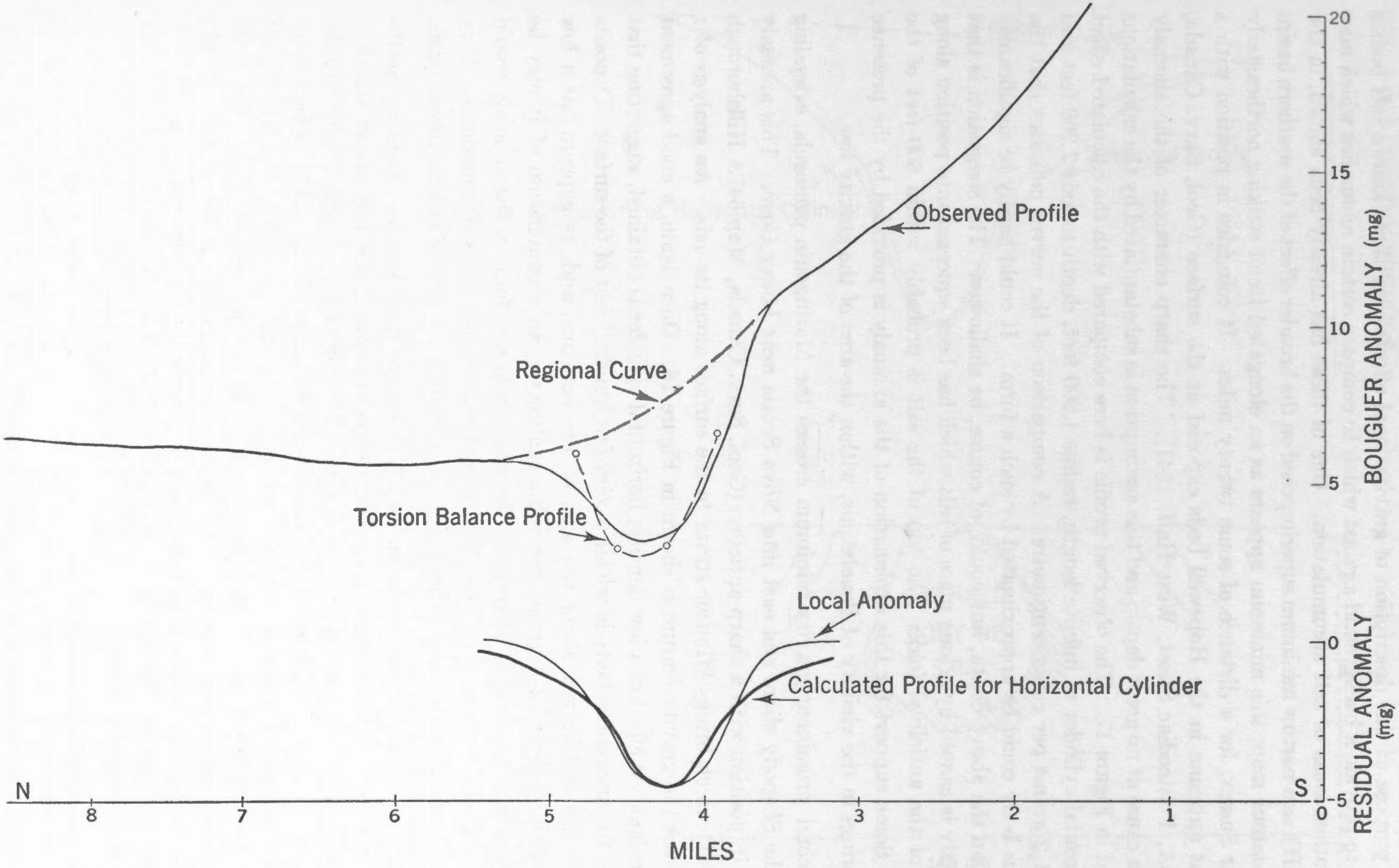


Fig. 16. Magnetic anomalies of the Moncton area.



SPRINGDALE PROFILE

Fig. 17. Gravity profile through Springdale, N.B.

The purpose of this description of gravitational effects over three known salt bodies has been to provide a background against which to compare certain anomalies which may indicate other areas of salt accumulation. One of these has already been shown, in the profile (GH), as a narrow minimum superimposed on the broader effect of the southern basin. On the contour map, this minimum appears as an elongated trend striking northeasterly from near Sussex, for a distance of some twenty miles. It coincides in position with a prominent anticline in the Hopewell beds exposed at the surface (Geol. Surv. Canada, Map 643A, Petitcodiac Sheet, West Half, 1941). The sharp character of the anomaly suggests a cause at no great depth, and this assumption is substantiated by the calculations illustrated in Figure 17. The observed profile is here compared with the calculated effect of a horizontal cylinder of infinite length, radius 1,600 feet, depth to axis 2,200 feet and density 2·2 grams per cubic centimetre. A comparison of the curves indicates that the anomalous body could be approximated by such a form. It could hardly be significantly deeper than the above depth, but could, of course, be shallower. The suggestion is that the anomaly is caused by a long mass of salt which has been squeezed into position along the axis of the anticlinal fold. The top of the salt is probably within 600 feet of the surface. Some support for this explanation of the anomaly is provided by the presence of salt springs in the vicinity of Penobsquis, within the area of the gravity low.

A second prominent gravity minimum crosses the Maringouin peninsula, extending west to the Shepody shore and east into Nova Scotia near Lower Cove. This anomaly coincides in position with a sharp anticline (Geol. Surv. Canada, Map 647A Hillsborough Sheet, 1941) which brings Windsor strata to the surface along its axis. An analysis of a profile across the gravity feature is shown in Figure 18. Once again, a good agreement with the calculated effect of a low density, horizontal cylinder is obtained, suggesting that the top of the anomalous body is within a very few hundred feet of the surface. Deposits of gypsum are well known along the axis of the anticline, and, as gypsum has a low density, of the order of 2·4 grams per cubic centimetre, an accumulation of it may be contributing to the anomaly. However, the magnitude and form of the anomaly would seem to demand a body with greater density contrast relative to its surroundings. Very probably, a mass of salt lies along the axis of the fold, for a distance of at least fifteen miles.

Finally, a similar narrow minimum may be seen north of Amherst, trending northeasterly for about ten miles across a low-lying region known as the Tantramar Marshes. The profile across the minimum, as given in Figure 19 shows it to be similar in form to the others studied. As before, calculations suggest the source of the anomaly to be a body whose upper surface is within a few hundred feet of the earth's surface, and which is of the order of 3,400 feet wide. If this body is a mass of salt, as seems probable, the exact structural relationships are not so evident as in the previous cases. However, the anomaly does appear to coincide with a recognized fault displacing the Carboniferous strata (Geol. Association of Canada, Tectonic Map of Canada, 1950) and the salt may have been concentrated along this fault.

These examples have shown the striking local gravity anomalies which appear to be produced by structures at relatively shallow depths within the Carboniferous column. Evidence has been presented which suggests they are caused by salt bodies squeezed into

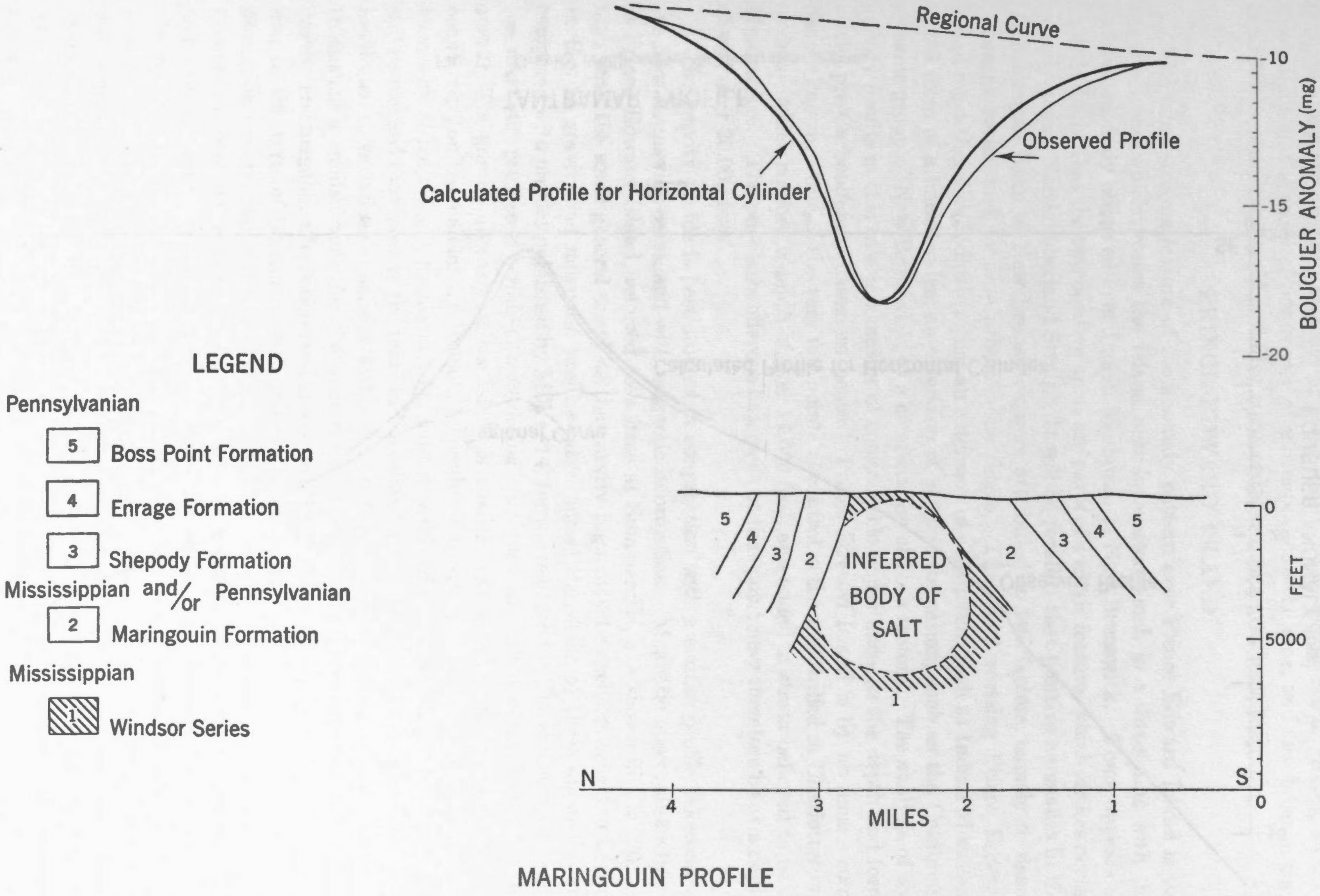
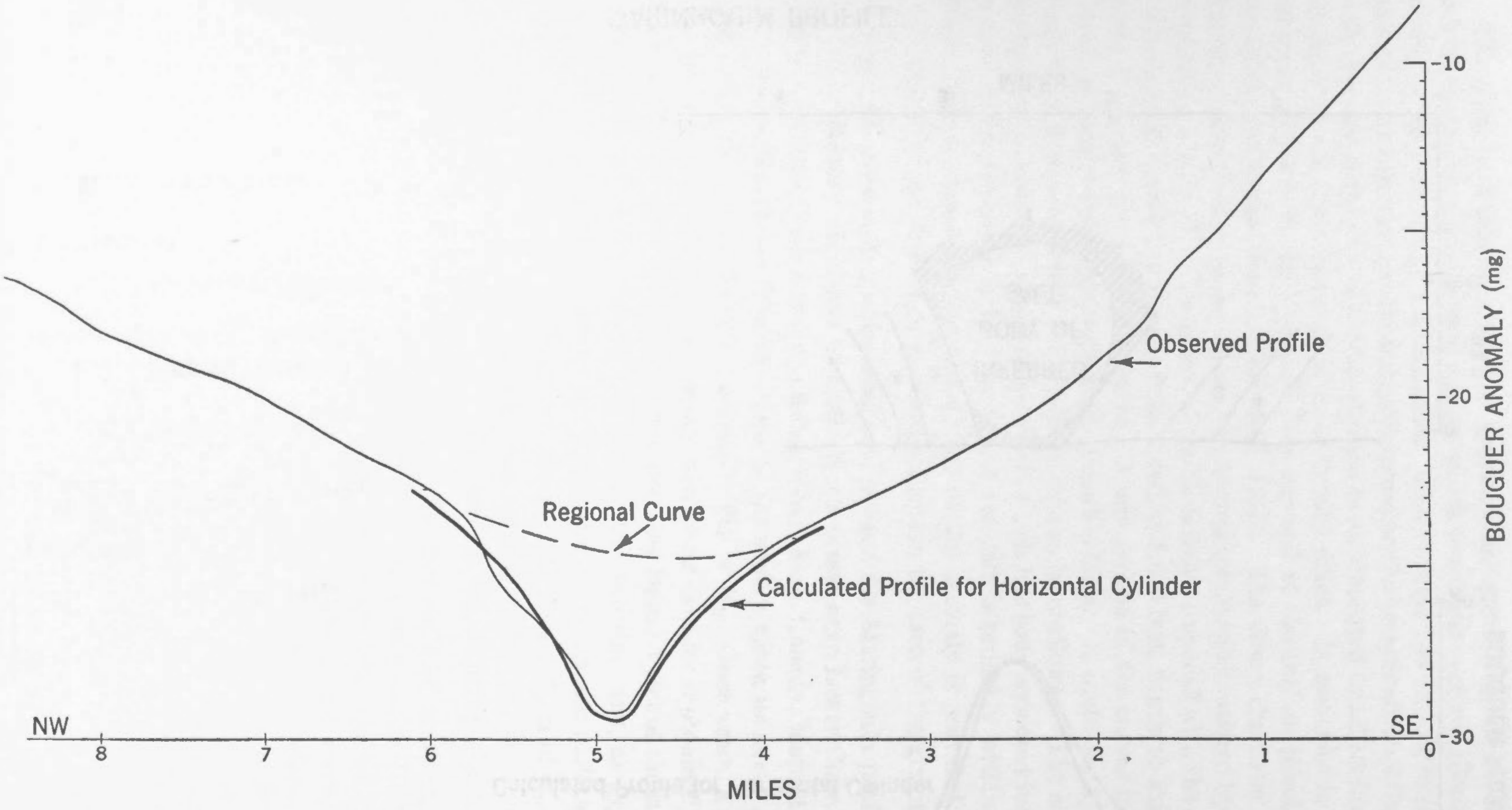


FIG. 18. Gravity profile and structure section along the Maringouin Peninsula.



TANTRAMAR PROFILE

FIG. 19. Gravity profile across the Tantramar region.

position along the axes of anticlines or along faults. The results are of interest as they throw light on the mode of occurrence of salt deposits in the area, and also because they indicate the practicability of outlining commercial deposits gravimetrically.

PRINCE EDWARD ISLAND

The most striking feature of the anomaly pattern over Prince Edward Island is the positive trend which crosses the Island near its westerly end, in a direct line with the positive anomaly observed over Indian Mountain in New Brunswick. There appears to be little doubt that the two positive areas are parts of a single feature, which strikes northeasterly across Northumberland Strait. It will be recalled that positive anomalies in the Carboniferous basin of New Brunswick were attributed to two factors, namely to dense basement rocks, and to pre-Carboniferous ridges. The trend crossing Prince Edward Island must therefore indicate either an extension of a structure such as Indian Mountain in the form of a buried ridge, an extension of a dense formation, such as the Coldbrook volcanic group of New Brunswick, or a combination of both factors. The analysis of the gravity results in this case is a matter of considerable importance, as the depth and form of the pre-Carboniferous basement beneath Prince Edward Island is by no means completely known. One of the very few points of control is the well drilled in Charlottetown harbour, which reached a depth of over 14,600 feet, and ended in strata believed to be of Windsor age. The pre-Carboniferous basement at that point may therefore be at a depth of well over 20,000 feet.

The gravity profile is best studied in conjunction with a similar profile taken along the New Brunswick coast, and with magnetic information. Magnetic observations taken in Prince Edward Island, referred to a base at Summerside, are shown in Fig. 20. A high with the same general trend as the gravity high may be seen crossing the Island. In Fig. 21 gravity and magnetic profiles taken across the strike of these anomalies are compared with profiles published by Miller (14) for the mainland. The similarity between the magnetic profiles is striking, considering that they are taken along lines 30 miles apart. The gravity anomaly on the Island is smaller in amplitude and narrower than its counterpart on the mainland. It could be produced by an uplift in the pre-Carboniferous basement of some eight thousand feet, with a width of about ten miles. However, it will be recalled that most of the relief in the related gravity anomaly on the mainland was attributed to variations in density within the pre-Carboniferous rocks, and it is reasonable to assume a similar cause for the anomaly on the Island. The suggestion is that the gravity and magnetic effects observed in western Prince Edward Island are at least partially due to the type of basement rock, namely volcanic and intrusive, of the Caledonian Mountain variety, rather than to basement relief alone. Nevertheless, as the rocks of the Caledonian Mountains type are characteristically resistant to erosion, a highland may well have existed along the line through western Prince Edward Island before and during the deposition of the Carboniferous sediments. If so, then a basement ridge could be expected to coincide in position with the gravity and magnetic anomalies. There is, in fact, a gentle anticlinal structure in the surface sedimentary rocks, which coincides closely in position with the axis of the gravity high. This feature was first described by Ells (5), and termed by him the Egmont anticline. It could possibly be a reflection of basement topography.

The axis of the gravity high on the Island is actually not directly in line with the exposed Caledonian Mountains on the mainland, but is more nearly in line with the more northerly ridge which forms Indian Mountain. There is, therefore, some suggestion from the anomaly map of a northward displacement of the system of denser rocks along the line of the Petitcodiac River.

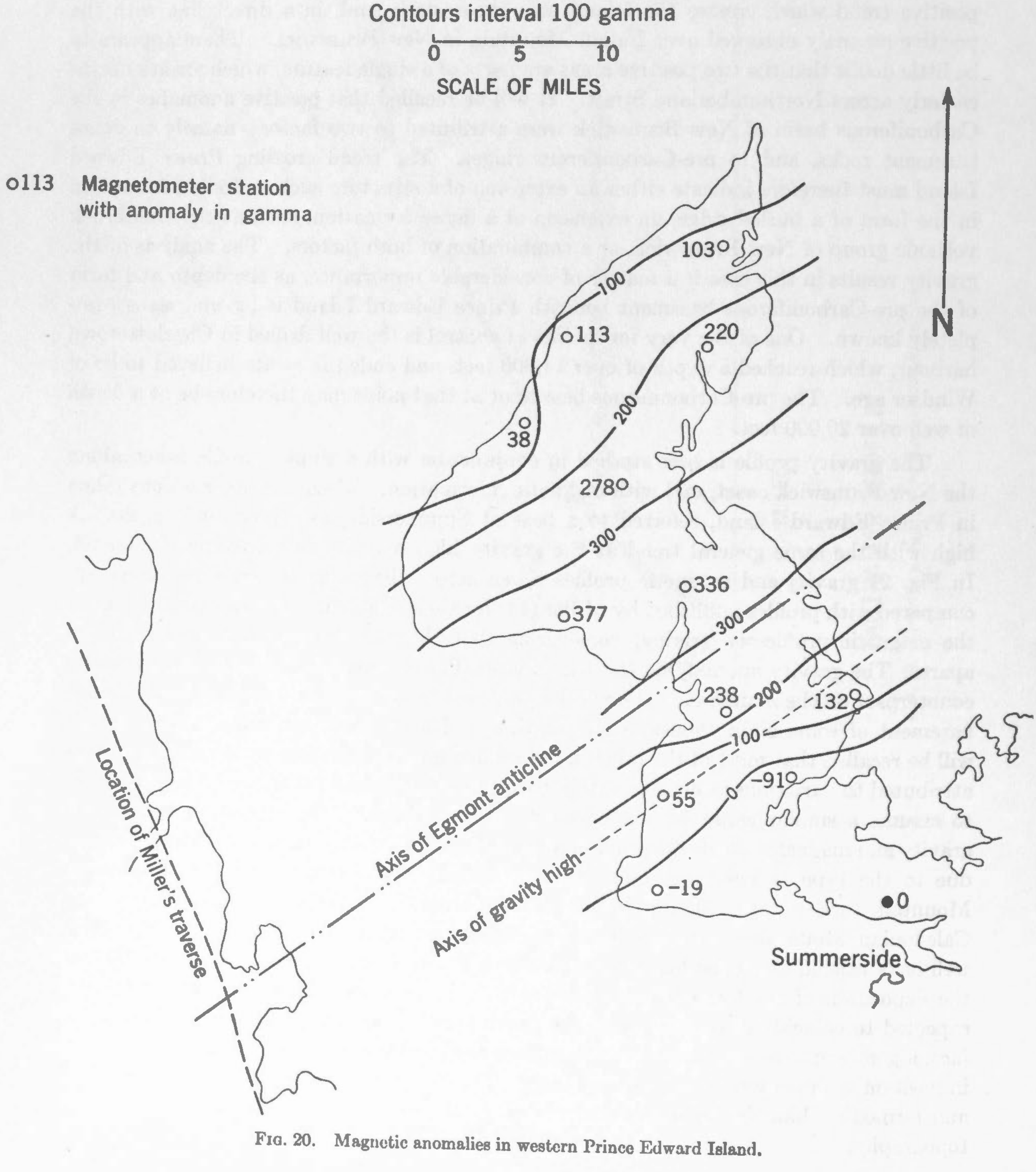


FIG. 20. Magnetic anomalies in western Prince Edward Island.

The greatest negative anomalies occur near the eastern end of the Island, in the form of a roughly circular minimum. Once again, it is difficult to say whether this is the result of a true thickening of the sedimentary column in this area, or of a region of lower density in the basement rocks. If the low is indicative of the thickest part of the basin, it suggests that the greatest basement depths are in the vicinity of St. Peter's, about thirty miles

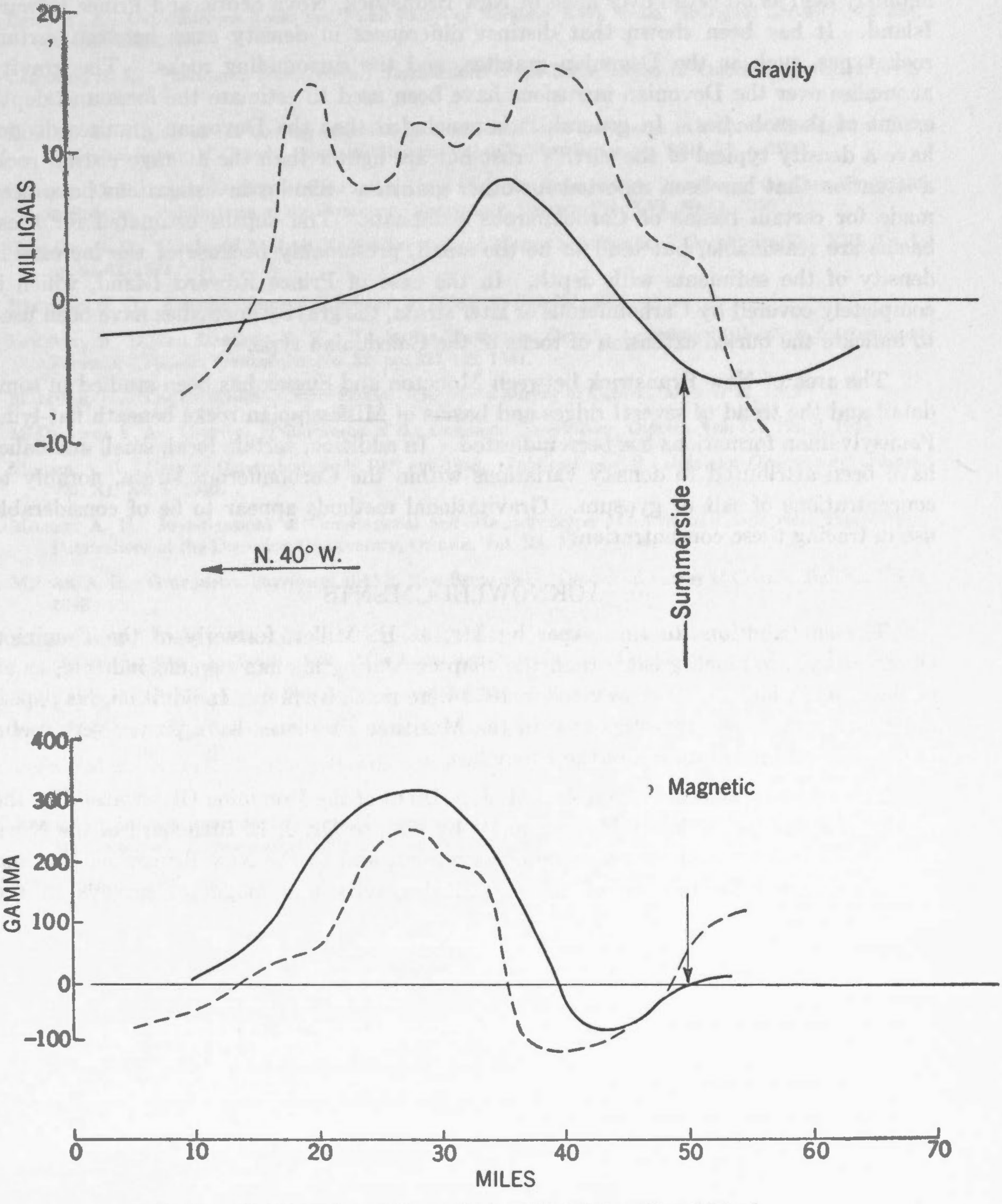


FIG. 21. Gravity and magnetic profiles in western Prince Edward Island.

northeast of Charlottetown. The sedimentary column may there have a considerably greater thickness than that indicated by the well drilled in Charlottetown harbour.

CONCLUSIONS

An interpretation has been offered for the major features of the Bouguer gravity anomaly field as observed over most of New Brunswick, Nova Scotia and Prince Edward Island. It has been shown that distinct differences in density exist between certain rock types, such as the Devonian granites, and the surrounding rocks. The gravity anomalies over the Devonian intrusions have been used to estimate the form and depth extent of these bodies. In general, it is concluded that the Devonian granites do not have a density typical of the earth's crust but are lighter than the average crustal rock, a situation that has been reported for other granites. Similar investigations have been made for certain basins of Carboniferous sediments. The depths estimated for these basins are reasonable, but tend to be too small, presumably because of the increase in density of the sediments with depth. In the case of Prince Edward Island, which is completely covered by Carboniferous or later strata, the gravity anomalies have been used to indicate the buried extension of rocks of the Caledonian type.

The area of New Brunswick between Moncton and Sussex has been studied in some detail and the trend of several ridges and basins of Mississippian rocks beneath flat-lying Pennsylvanian formations has been indicated. In addition, certain local, small anomalies have been attributed to density variations within the Carboniferous strata, notably to concentrations of salt or gypsum. Gravitational methods appear to be of considerable use in tracing these concentrations.

ACKNOWLEDGMENTS

The contributions to this paper by Mr. A. H. Miller, formerly of the Dominion Observatory, are much greater than the chapter bearing his name would indicate, as all of the observations in years previous to 1950 were made by him. In addition, his papers on earlier geophysical investigations in the Maritime Provinces have proven very useful in the over-all interpretation of the anomalies.

The writer is indebted also to Dr. M. J. S. Innes of the Dominion Observatory for the results of a number of determinations made by him, to Dr. J. E. Blanchard of the Nova Scotia Research Council for magnetic observations, and to the New Brunswick Gas and Oilfields Limited for the use of their detailed gravity and magnetic surveys in the Moncton area.

BIBLIOGRAPHY

1. Alcock, F. J. Geology of Saint John Region, New Brunswick, Geological Survey of Canada, Memoir 216, 1940.

2. Bell, W. A. Horton-Windsor District, Nova Scotia, Geological Survey of Canada, Memoir 155, 1929.

3. Bell, W. A. Carboniferous Rocks and Fossil Floras of Northern Nova Scotia, Geological Survey of Canada, Memoir 238, 1946.

4. Cameron, H. L. Faulting in Nova Scotia. Transactions of the Royal Society of Canada, Vol. XLIII, Series III, 1949.

5. Ells, R. W. Report on the Geology of Prince Edward Island with References to Proposed Borings for Coal. Geological Survey of Canada, Summary Report, Vol. XV, New Series, pp. 369A-379A, 1903.

6. Garland, G. D. Interpretations of Gravitational and Magnetic Anomalies on Traverses in the Canadian Shield in Ontario. Publications of the Dominion Observatory, Ottawa, Vol. XVI, No. 1, 1950.

7. Garland, G. D. Combined Analysis of Gravitational and Magnetic Anomalies. Geophysics, Vol. XVI, No. 1, pp. 51-62, 1951.

8. Hedberg, H. D. American Journal of Science, 31 (184), pp. 241-287, 1936.

9. Lambert, W. D. and Darling, F. W. Tables for Theoretical Gravity According to the New International Formula. Bulletin Geodesique, No. 32, pp. 327-340, 1931.

10. Malcolm, W. The Goldfields of Nova Scotia. Geological Survey of Canada, Memoir 20, 1912.

11. McDiarmid, F. A. Gravity. Publications of the Dominion Observatory, Ottawa, Vol. III, No. 9, 1918.

12. Miller, A. H. Gravity Determinations in 1937 and 1938. Publications of the Dominion Observatory, Ottawa, Vol. XI, No. 5, 1940.

13. Miller, A. H. Investigations of Gravitational and Magnetometric Methods of Geophysical Prospecting. Publications of the Dominion Observatory, Ottawa, Vol. XI, No. 6, 1940.

14. Miller, A. H. Gravimetric Surveys of 1944 in New Brunswick. Geological Survey of Canada, Bulletin No. 6, 1946.

15. Miller, A. H. Gravity Anomalies in New Brunswick and Nova Scotia. Abstracts of Papers, Royal Society of Canada, 1946. In Transactions of the Royal Society of Canada, Third Series, Vol. XL, p. 170, 1946.

16. Nettleton, L. L. Geophysical Prospecting for Oil, McGraw-Hill, New York, pp. 101-102, 1940.

17. Powers, Sidney. The Acadian Triassic. Journal of Geology. Vol. 24, pp. 1-26, 105-122, and 254-268, 1916.

18. Putnam, G. R. Appendix No. 6, Report of the United States Coast and Geodetic Survey for 1896. Washington, 1897.

19. Reich, H. Die Bedeutung der finnischen Schweremessungen für die angewandte Geophysik. Gerland's Beiträge zür Geophysik, Ergänzungshefte für angewandte Geophysik, Band 2, pp. 1-13, 1932.

20. Schuchert, C. Significance of the Taconic Orogeny. Bulletin of the Geological Society of America, Vol. 36, pp. 342-350, 1925.

21. Shaw, W. Descriptive Notes, Geological Survey of Canada, Preliminary Map 51-11, Springhill Sheet, 1951.

22. Swick, C. H. Pendulum Gravity Measurements and Isostatic Reductions. United States Coast and Geodetic Survey, Special Publication No. 232, 1942.

23. Weeks, L. J. Londonderry and Bass River Map-areas, Colchester and Hants Counties, Nova Scotia. Geological Survey of Canada, Memoir 245, 1948.

24. Williams, N. Y. Arisaig-Antigonish District, Nova Scotia, Geological Survey of Canada, Memoir 60, 1914.

25. Woollard, G. P. Report of the Special Committee on the Geophysical and Geological Study of the Continents, 1950-1951. Transactions of the American Geophysical Union, Vol. 32, pp. 634-647, 1951.

26. Young, G. A. George River. Geological Survey of Canada, Guide Book No. 1, pp. 266-276, 1913.

APPENDIX

Principal Facts for Gravity Stations

in

NEW BRUNSWICK

NOVA SCOTIA

PRINCE EDWARD ISLAND

PRINCIPAL FACTS FOR GRAVITY STATIONS—NEW BRUNSWICK

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name								Free Air	Bouguer
			°	′	°	′	Ft.			
1	St. Andrews	1950	67	02·7	45	04·2	23	980·6423	0·0088	0·0079
2	Pennfield	1950	66	40·1	45	07·5	227	·6229	·0037	− ·0041
3	St. George	1950	66	49·1	45	08·0	89	·6375	·0045	·0014
4	Lepreau	1950	66	28·0	45	10·2	78	·6369	− ·0005	− ·0032
5	Bocabec Cove	1950	66	59·2	45	10·9	46	·6458	·0043	·0027
6	Musquash	1950	66	20·0	45	11·2	17	·6483	·0037	·0031
7	(Bartlett)	1950	67	08·3	45	12·5	69	·6387	− ·0030	− ·0054
8	St. Stephen	1950	67	15·5	45	13·0	84	·6296	− ·0115	− ·0143
9	Spruce Lake	1950	66	10·5	45	13·2	205	·6581	·0281	·0211
10	Black River	1945	65	47·1	45	15·9	27	·6704	·0196	·0187
11	Saint John	1950	66	05·1	45	16·0	114	980·6658	0·0230	0·0192
12	Moore's Mills	1950	67	16·4	45	17·6	297	·6059	− ·0220	− ·0321
13	Grand Bay	1947	66	11·4	45	18·5	61	·6631	·0116	·0095
14	Fairfield	1945	65	41·2	45	20·3	349	·6545	·0274	·0155
15	Quaco	1945	65	33·5	45	20·5	25	·6626	·0048	·0039
16	Loch Lomond	1945	65	52·3	45	20·5	318	·6546	·0243	·0135
17	Woodman Point	1944	66	14·1	45	22·2	30	·6649	·0049	·0039
18	(Lynnfield)	1950	67	16·2	45	22·6	438	·6132	− ·0090	− ·0240
19	Rothesay	1947	65	59·9	45	23·4	231	·6733	·0109	·0101
20	Wood Lake	1945	65	35·4	45	24·9	527	·6462	·0289	·0109
21	Welsford	1945	66	20·9	45	27·3	76	980·6556	−0·0078	−0·0103
22	Hanford Brook	1945	65	37·5	45	27·5	261	·6694	·0231	·0143
23	Glennwood	1944	66	07·1	45	29·4	44	·6855	·0159	·0144
24	(Ste. Croix)	1950	67	19·9	45	30·3	413	·6342	− ·0020	− ·0161
25	Hampton Station	1944	65	49·7	45	31·6	27	·6867	·0123	·0114
26	Hillsdale	1945	65	33·7	45	32·4	350	·6749	·0297	·0178
27	Enniskillen	1945	66	30·0	45	32·5	112	·6582	− ·0096	− ·0134
28	Ste. Croix	1950	67	25·7	45	34·0	382	·6338	− ·0109	− ·0239
29	Hammondvale	1944	65	30·2	45	34·4	513	·6726	·0397	·0222
30	Erandale	1944	66	02·9	45	35·6	22	·6929	·0120	·0112
31	Alma	1945	64	57·1	45	35·7	140	980·6908	0·0209	0·0161
32	McAdam	1950	67	19·8	45	35·7	459	·6270	− ·0129	− ·0285
33	Hastings	1945	65	00·2	45	36·4	995	·6439	·0533	·0194
34	(Jeffrey)	1944	65	29·6	45	36·6	461	·6713	·0303	·0146
35	Walton Lake	1947	65	19·2	45	36·9	730	·6563	·0400	·0152
36	Bennett Lake	1945	65	04·7	45	37·5	880	·6531	·0501	·0201
37	Jeffrey	1944	65	29·6	45	37·8	404	·6748	·0266	·0128
38	Dennis Beach	1945	64	51·3	45	38·0	90	·6879	·0098	·0067
39	(McAdam)	1950	67	14·5	45	38·0	519	·6304	− ·0074	− ·0251
40	(Walton Lake)	1947	65	20·0	45	38·1	746	·6560	·0394	·0141
41	Norton	1944	65	41·9	45	38·3	52	980·6921	0·0101	0·0083
42	Little Ridge	1945	64	44·9	45	38·5	200	·6760	·0075	·0007
43	(Walker Settlement)	1947	65	24·0	45	38·5	429	·6748	·0278	·0133
44	Walker Settlement	1947	65	22·7	45	38·8	875	·6486	·0431	·0133
45	(Hawke's Bridge)	1947	65	19·6	45	39·1	548	·6686	·0319	·0133
46	(Magagnadavic)	1950	67	07·7	45	39·3	408	·6432	− ·0069	− ·0208
47	(Hawke's Bridge)	1947	65	19·8	45	39·4	444	·6744	·0275	·0123
48	(Jeffrey)	1944	65	30·9	45	39·4	247	·6821	·0166	·0082
49	(Rockville)	1947	65	24·5	45	39·7	307	·6828	·0226	·0121
50	Lakeview	1945	65	08·6	45	39·7	997	·6498	·0545	·0205

PRINCIPAL FACTS FOR GRAVITY STATIONS—NEW BRUNSWICK—*Continued*

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name								Free Air	Bouguer
			°	′	°	′	Ft.			
51	(Hawke's Bridge)...........	1947	65	20·4	45	39·8	398	980·6795	0·0277	0·0141
52	(Rockville).................	1947	65	24·6	45	40·0	322	·6820	·0227	·0118
53	Hawke's Bridge............	1947	65	21·2	45	40·2	344	·6823	·0248	·0130
54	Mersereau Brook...........	1945	66	27·0	45	40·4	257	·6674	·0014	— ·0074
55	Queenstown...............	1944	66	06·1	45	40·7	27	·6999	·0018	·0109
56	(Chamber's Settlement)......	1947	65	18·3	45	40·8	740	·6666	·0454	·0202
57	Waterford..................	1947	65	22·3	45	40·9	281	·6855	·0210	·0114
58	(Aiton).....................	1947	65	33·4	45	41·1	131	·6897	·0108	·0063
59	(Sussex)...................	1944	65	30·8	45	41·3	175	·6865	·0115	·0055
60	(Rockville).................	1947	65	25·0	45	41·4	180	·6882	·0134	·0073
61	(Waterford)................	1947	65	24·0	45	41·5	251	980·6853	0·0171	0·0085
62	Rockville..................	1947	65	25·9	45	41·5	198	·6875	·0143	·0076
63	(Cedar Camp)..............	1947	65	18·9	45	41·8	487	·6847	·0382	·0216
64	(Sussex Corner)............	1947	65	28·8	45	42·1	137	·6894	·0095	·0048
65	(Sussex Corner)............	1944	65	28·8	45	42·3	108	·6919	·0090	·0053
66	Apohaqui..................	1947	65	36·2	45	42·3	75	·6931	·0071	·0045
67	(Sussex Corner)............	1947	65	28·8	45	42·4	104	·6914	·0080	·0044
68	Urney.....................	1947	65	22·2	45	42·5	572	·6678	·0283	·0088
69	(Aiton)....................	1947	65	33·7	45	42·5	105	·6927	·0092	·0057
70	Sussex Corner..............	1947	65	28·9	45	42·6	94	·6919	·0072	·0041
71	(Cedar Camp)..............	1947	65	19·0	45	42·7	892	980·6628	0·0531	0·0227
72	Aiton......................	1947	65	33·1	45	42·7	61	·6948	·0069	·0048
73	(Urney)....................	1947	65	21·3	45	43·2	444	·6782	·0256	·0104
74	Sussex.....................	1944	65	30·6	45	43·2	70	·6944	·0066	·0042
75	(Sussex Corner)............	1944	65	27·5	45	43·4	133	·6928	·0106	·0061
76	Sussex.....................	1947	65	30·9	45	43·4	70	·6945	·0064	·0041
77	Harvey.....................	1945	64	42·6	45	43·5	59	·6909	·0016	— ·0004
78	Sussex.....................	1944	65	31·1	45	43·5	68	·6957	·0073	·0050
79	(Apohaqui).................	1947	65	36·7	45	43·5	80	·6950	·0077	·0050
80	(Mechanic's Settlement).....	1947	65	11·6	45	43·7	1,009	·6605	·0603	·0259
81	(Sussex)...................	1944	65	32·3	45	43·7	67	980·6981	0·0093	0·0070
82	(Sussex)...................	1947	65	32·3	45	43·7	60	·6977	·0082	·0061
83	(Mechanic's Settlement).....	1944	65	11·7	45	43·8	1,000	·6604	·0592	·0251
84	(Picadilly).................	1947	65	21·6	45	43·8	369	·6842	·0236	·0110
85	Harvey.....................	1950	67	00·0	45	43·8	492	·6403	— ·0087	— ·0255
86	(Mechanic's Settlement).....	1947	65	10·7	45	43·9	1,100	·6551	·0632	·0257
87	(Mechanic's Settlement).....	1944	65	14·1	45	43·9	950	·6667	·0607	·0283
88	(South Branch).............	1947	65	18·2	45	43·9	466	·6947	·0431	·0272
89	(Sussex)...................	1947	65	33·3	45	44·1	248	·6895	·0171	·0086
90	(Mechanic's Settlement).....	1947	65	09·6	45	44·2	1,149	·6537	·0659	·0267
91	Lower Millstream...........	1947	65	36·9	45	44·2	54	980·6975	0·0067	0·0048
92	(Plumweseep)..............	1947	65	26·8	45	44·3	82	·6945	·0062	·0034
93	(Sussex Corner)............	1944	65	26·8	45	44·4	80	·6951	·0065	·0038
94	(Church Hill)...............	1947	65	08·0	45	44·6	1,148	·6542	·0657	·0266
95	(Picadilly).................	1947	65	22·6	45	44·6	272	·6909	·0200	·0108
96	(Plumweseep)..............	1947	65	26·3	45	44·6	69	·6954	·0054	·0030
97	Albert.....................	1945	64	44·2	45	44·7	24	·7044	·0101	·0092
98	(Sussex)...................	1944	65	34·1	45	44·7	225	·6903	·0149	·0072
99	(Mechanic's Settlement).....	1947	65	10·7	45	44·9	1,109	·6547	·0620	·0242
100	Plumweseep................	1947	65	27·5	45	44·9	68	·6965	·0059	·0037

PRINCIPAL FACTS FOR GRAVITY STATIONS—NEW BRUNSWICK—*Continued*

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name								Free Air	Bouguer
			°	′	°	′	Ft.			
101	(Mechanic's Settlement).....	1947	65	14·6	45	45·0	907	980·6679	0·0560	0·0251
102	(South Branch).............	1947	65	18·0	45	45·0	313	·7002	·0324	·0218
103	(South Branch).............	1944	65	18·0	45	45·0	310	·6999	·0319	·0213
104	(Penobsquis)...............	1944	65	25·6	45	45·0	135	·6933	·0088	·0042
105	Riverside..................	1947	64	43·7	45	45·2	56	·7035	·0114	·0095
106	Woodside...................	1945	66	30·3	45	45·2	194	·6740	− ·0052	− ·0118
107	(Goshen)...................	1947	65	10·3	45	45·3	1,042	·6590	·0594	·0239
108	(McCully)..................	1947	65	25·1	45	45·3	85	·6951	·0055	·0027
109	Ryan's Corner..............	1947	65	30·1	45	45·3	107	·6984	·0109	·0073
110	Church Corner..............	1947	65	04·7	45	45·4	582	·6878	·0448	·0250
111	(Goshen)...................	1947	65	09·6	45	45·4	1,006	980·6620	0·0589	0·024
112	(Penobsquis)...............	1947	65	23·6	45	45·4	132	·6948	·0095	·0050
113	(Ryan's Corner)............	1947	65	29·7	45	45·5	160	·6964	·0136	·0082
114	(Penobsquis)...............	1947	65	23·7	45	45·6	120	·6950	·0083	·0042
115	(Plumweseep)...............	1947	65	27·6	45	45·6	133	·6955	·0100	·0054
116	(Millstream)...............	1944	65	34·6	45	45·6	252	·6876	·0133	·0047
117	(Goshen)...................	1947	65	13·8	45	45·7	756	·6742	·0471	·0214
118	(Sprindale)................	1944	65	18·7	45	45·7	267	·6979	·0248	·0157
119	(Goshen)...................	1947	65	12·5	45	45·8	672	·6785	·0434	·0205
120	(Penobsquis)...............	1947	65	23·8	45	45·8	146	·6922	·0076	·0027
121	Hopewell Hill..............	1945	64	41·5	45	45·9	23	980·6925	−0·0037	−0·0045
122	(Hillside).................	1947	65	02·2	45	45·9	457	·6918	·0364	·0208
123	(Goshen)...................	1947	65	11·2	45	45·9	537	·6858	·0379	·0196
124	(McCully)..................	1947	65	25·3	45	45·9	70	·6993	·0075	·0051
125	(Penobsquis)...............	1947	65	23·8	45	46·0	147	·6926	·0077	·0027
126	(Penobsquis)...............	1947	65	23·9	45	46·0	146	·6921	·0071	·0022
127	(Millstream)...............	1944	65	34·7	45	46·0	166	·6919	·0088	·0032
128	(McCully)..................	1947	65	25·6	45	46·1	85	·6992	·0084	·0055
129	(Church Corner)............	1947	65	05·3	45	46·2	505	·6915	·0401	·0229
130	(Goshen)...................	1947	65	09·6	45	46·2	823	·6698	·0483	·0203
131	(Plumweseep)...............	1947	65	27·9	45	46·2	283	980·6893	0·0170	0·0074
132	(Shepody)..................	1947	64	39·2	45	46·3	94	·6836	− ·0067	− ·0099
133	Springdale.................	1944	65	19·3	45	46·4	223	·6977	·0195	·0119
134	(Riverside)................	1947	64	43·9	45	46·6	451	·6930	·0359	·0206
135	(Hillside).................	1947	65	01·4	45	46·6	408	·6948	·0337	·0198
136	Penobsquis.................	1944	65	22·4	45	46·6	100	·6958	·0057	·0023
137	Smith's Creek..............	1947	65	28·8	45	46·6	103	·7021	·0123	·0088
138	Daniel.....................	1947	64	38·2	45	46·7	32	·6844	− ·0123	− ·0134
139	Daniel.....................	1944	64	38·2	45	46·7	58	·6827	− ·0115	− ·0135
140	(Springdale)...............	1944	65	19·7	45	46·8	210	·6949	·0150	·0078
141	Penobsquis.................	1947	65	23·1	45	46·9	92	980·7001	0·0088	0·0056
142	(Goshen)...................	1947	65	08·9	45	47·0	588	·6794	·0346	·0146
143	(Springdale)...............	1944	65	20·2	45	47·0	167	·6940	·0096	·0039
144	Gordon Falls...............	1947	65	05·8	45	47·1	442	·6946	·0359	·0208
145	(Smith's Creek)............	1947	65	29·3	45	47·1	137	·7002	·0128	·0082
146	(Penobsquis)...............	1944	65	20·6	45	47·2	185	·6932	·0103	·0040
147	(Hopewell Hill)............	1947	64	40·4	45	47·3	170	·6964	·0118	·0060
148	(Meadow)...................	1947	65	01·4	45	47·3	756	·6721	·0426	·0169
149	(Goshen)...................	1947	65	10·2	45	47·3	451	·6864	·0282	·0129
150	(Riverside)................	1947	64	44·7	45	47·4	881	·6689	·0511	·0211

PRINCIPAL FACTS FOR GRAVITY STATIONS—NEW BRUNSWICK—*Continued*

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name								Free Air	Bouguer
			°	′	°	′	Ft.			
151	(Elgin)	1947	65	07·7	45	47·4	486	980·6846	0·0296	0·0131
152	(Long Creek)	1950	66	54·8	45	47·4	467	·6504	— ·0064	— ·0223
153	(Penobsquis)	1944	65	20·9	45	47·6	170	·6967	·0118	·0060
154	(Prosser Brook)	1947	64	59·4	45	47·8	566	·6893	·0412	·0220
155	Elgin	1947	65	06·8	45	47·8	357	·6934	·0257	·0135
156	(Five Points)	1944	65	19·2	45	47·8	171	·6960	·0108	·0050
157	(Mount Hebron)	1947	65	30·8	45	47·8	347	·6860	·0173	·0055
158	(Pleasant Ridge)	1947	65	38·2	45	48·0	207	·6898	·0077	·0006
159	(Rosevale)	1947	64	45·0	45	48·1	1,092	·6524	·0533	·0161
160	(Prosser Brook)	1947	64	58·4	45	48·2	911	·6678	·0516	·0206
161	(Goshen)	1947	65	10·2	45	48·2	408	980·6902	0·0267	0·0059
162	(Five Points)	1947	65	18·1	45	48·2	181	·6947	·0098	·0037
163	(Millstream)	1944	65	38·2	45	48·2	233	·6894	·0094	·0014
164	(Mount Pisgah)	1947	65	28·0	45	48·3	169	·7003	·0141	·0084
165	(Mount Hebron)	1947	65	32·1	45	48·3	287	·6897	·0146	·0048
166	Centre Millstream	1947	65	35·4	45	48·4	135	·6964	·0065	·0029
167	Gowland Mountain	1947	65	01·9	45	48·5	982	·6600	·0500	·0165
168	(Cape Station)	1944	64	36·3	45	48·7	70	·6971	·0010	— ·0014
169	(Elgin)	1947	65	06·6	45	48·7	352	·6925	·0229	·0109
170	(Pleasant Ridge)	1947	65	36·1	45	48·7	166	·6943	·0072	·0016
171	Cape Station	1947	64	36·8	45	48·8	75	980·7016	0·0058	0·0033
172	(Gowland Mountain)	1947	65	02·3	45	48·8	1,099	·6536	·0542	·0167
173	(Fenwick)	1944	65	40·0	45	48·9	600	·6734	·0268	·0064
174	(Curryville Station)	1947	64	39·1	45	49·0	537	·6841	·0315	·0132
175	(Mapleton)	1947	65	04·7	45	49·0	450	·6894	·0286	·0133
176	Pleasant Ridge	1947	65	36·8	45	49·0	365	·6818	·0006	·0006
177	Rosevale	1947	64	45·2	45	49·2	1,031	·6615	·0551	·0200
178	(Prosser Brook)	1947	64	58·2	45	49·2	872	·6706	·0492	·0195
179	(Goshen)	1947	65	10·1	45	49·2	384	·6874	·0201	·0070
180	Five Points	1944	65	17·8	45	49·2	195	·6970	·0119	·0053
181	Blakney Station	1947	65	06·4	45	49·3	323	980·6949	0·0217	0·0107
182	(Portage Vale)	1947	65	11·2	45	49·4	323	·6902	·0169	·0059
183	(Mapleton)	1947	65	01·8	45	49·5	995	·6589	·0486	·0147
184	Mapleton	1947	65	03·1	45	49·5	566	·6851	·0344	·0152
185	(Portage Vale)	1947	65	12·2	45	49·6	293	·6912	·0148	·0048
186	(Newton)	1947	65	27·2	45	49·6	146	·7027	·0124	·0075
187	(Portage Vale)	1947	65	13·2	45	49·7	322	·6896	·0159	·0049
188	(The Rocks)	1944	64	35·0	45	49·8	125	·6993	·0068	·0025
189	(Five Points)	1947	65	16·2	45	49·8	237	·6946	·0126	·0045
190	(Five Points)	1947	65	18·1	45	49·8	254	·6951	·0147	·0060
191										
192	Marven Station	1947	65	19·2	45	49·9	141	·7022	0·0110	0·0062
193	(Fenwick)	1944	65	42·2	45	49·9	492	·6814	·0232	·0064
194	Amherst	1944	64	12·8	45	50·0	70	·6930	— ·0050	— ·0074
195	(Portage Vale)	1947	65	13·3	45	50·0	270	·6928	·0136	·0044
196	(Pollett River)	1947	65	06·3	45	50·2	319	·6955	·0206	·0097
197	(Carsonville)	1947	65	32·4	45	50·2	332	·6873	·0136	·0023
198	(Centre Millstream)	1947	65	34·5	45	50·2	158	·6954	·0046	·0000
199	Curryville Station	1947	64	38·1	45	50·3	103	·7155	·0201	·0166
200	(Prosser Brook)	1947	64	57·7	45	50·3	454	·6931	·0297	·0152

PRINCIPAL FACTS FOR GRAVITY STATIONS—NEW BRUNSWICK—*Continued*

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name								Free Air	Bouguer
			°	′	°	′	Ft.			
201	(Pleasant Vale)	1947	65	01·5	45	50·3	541	980·6864	0·0322	0·0138
202	(Mapleton)	1947	65	03·3	45	50·3	617	·6787	·0316	·0106
203	(Pleasant Ridge)	1947	65	36·2	45	50·3	286	·6894	·0112	·0015
204	(Rosevale)	1947	64	45·7	45	50·4	1,111	·6607	·0600	·0222
205	(Prosser Brook)	1947	64	52·8	45	50·4	934	·6666	·0492	·0174
206	(Prosser Brook)	1947	64	55·3	45	50·4	469	·6927	·0316	·0156
207	(Five Points)	1947	65	15·2	45	50·4	276	·6925	·0133	·0039
208	Newton	1947	65	25·9	45	50·4	194	·7012	·0142	·0076
209	Prosser Brook	1947	64	57·2	45	50·5	428	·6951	·0300	·0154
210	Pleasant Vale	1947	65	00·3	45	50·5	346	·6976	·0247	·0130
211	Portage Vale	1944	65	13·6	45	50·5	255	980·6942	0·0128	0·0041
212	Portage Vale	1947	65	13·6	45	50·5	269	·6936	·0135	·0043
213	(Prosser Brook)	1947	64	57·5	45	50·6	381	·6979	·0282	·0153
214	(Portage Vale)	1944	65	13·5	45	50·6	280	·6931	·0139	·0044
215	(Five Points)	1944	65	16·7	45	50·6	150	·7016	·0102	·0051
216	(Gibbon)	1947	65	34·0	45	50·6	178	·6946	·0058	− ·0002
217	Hopewell Cape	1944	64	34·6	45	50·7	100	·7038	·0075	·0041
218	Upper Gagetown	1944	66	14·7	45	50·7	41	·6909	− ·0109	− ·0123
219	(Rosevale)	1947	64	47·4	45	50·8	1,096	·6637	·0610	·0237
220	Jordan Mountain	1947	65	28·7	45	50·8	75	·6931	− ·0056	− ·0082
221	(Pleasant Ridge)	1947	65	37·9	45	50·8	607	980·6727	0·0240	0·0033
222	(Albert Mines)	1947	64	38·7	45	50·9	162	·7140	·0232	·0177
223	(Prosser Brook)	1947	64	57·7	45	51·0	360	·6995	·0273	·0150
224	(Fenwick)	1944	65	44·0	45	51·0	375	·6855	·0147	·0019
225	Fort Lawrence	1947	64	15·5	45	51·1	61	·6877	− ·0129	− ·0149
226	(Rosevale)	1947	64	50·9	45	51·1	559	·6909	·0372	·0181
227	(Pollett River)	1947	65	06·4	45	51·2	360	·6936	·0211	·0088
228	(Portage Vale)	1944	65	13·8	45	51·2	543	·6775	·0222	·0037
229	(Portage Vale)	1947	65	13·9	45	51·2	562	·6774	·0238	·0047
230	Oromocto	1944	66	28·5	45	51·2	24	·6923	− ·0118	− ·0127
231	(Prosser Brook)	1947	64	57·8	45	51·4	340	980·6997	0·0250	0·0134
232	Rosevale	1947	64	49·0	45	51·5	860	·6731	·0471	·0178
233	(Hopewell Cape)	1944	64	34·8	45	51·6	76	·7078	·0079	·0054
234	(Albert Mines)	1947	64	40·9	45	51·6	205	·7128	·0251	·0181
235	(Parkindale)	1947	65	00·3	45	51·6	481	·6884	·0266	·0103
236	Carsonville	1947	65	31·3	45	51·6	401	·6827	·0134	− ·0002
237	(Rosevale)	1947	64	51·4	45	51·6	442	·6968	·0314	·0163
238	(Albert Mines)	1947	64	40·2	45	51·7	269	·7088	·0269	·0177
239	(Anagance Corner)	1947	65	14·5	45	51·7	302	·6932	·0144	·0041
240	Knightville	1947	65	22·1	45	51·7	255	·6988	·0156	·0069
241	Albert Mines	1947	64	39·8	45	51·8	199	980·7121	0·0235	0·0167
242	(Pollett River)	1947	65	06·3	45	51·8	308	·6966	·0183	·0078
243	(Jordan Mountain)	1947	65	28·5	45	51·8	513	·6837	·0246	·0072
244	(Gibbon)	1947	65	32·9	45	51·8	223	·6921	·0058	·0018
245	(Parkindale)	1947	64	58·8	45	51·9	334	·6992	·0231	·0117
246	(Pollett River)	1947	65	03·8	45	51·9	446	·6896	·0240	·0089
247	Parkindale	1947	65	00·9	45	52·0	412	·6926	·0237	·0097
248	(Knightville)	1947	65	22·8	45	52·0	251	·7007	·0167	·0082
249	(Rosevale)	1947	64	48·8	45	52·1	616	·6886	·0387	·0178
250	Parkindale	1947	64	59·1	45	52·1	327	·6997	·0227	·0115

PRINCIPAL FACTS FOR GRAVITY STATIONS—NEW BRUNSWICK—*Continued*

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name		°	′	°	′	Ft.		Free Air	Bouguer
251	(Fort Lawrence)............	1947	64	14·4	45	52·2	85	980·6857	−0·0142	−0·0171
252	(Berryton)................	1947	64	51·8	45	52·2	384	·6987	·0269	·0138
253	Anagance.................	1947	65	15·2	45	52·2	161	·7033	·0105	·0051
254	(White Mountain)...........	1947	65	26·8	45	52·2	611	·6768	·0264	·0056
255	Long Creek................	1950	66	55·6	45	52·2	45	·6909	− ·0129	− ·0144
256	Aulac.....................	1944	64	16·9	45	52·3	74	·6780	− ·0231	− ·0257
257	Frosty Hollow..............	1944	64	25·9	45	52·3	202	·6800	− ·0091	− ·0160
258	(Hopewell Cape)............	1944	64	36·0	45	52·3	70	·7151	·0136	·0112
259	(Parkindale)...............	1947	65	02·6	45	52·3	394	·6931	·0221	·0086
260	(Anagance Ridge)...........	1947	65	18·7	45	52·3	400	·6888	·0183	·0047
261	(Knightville)...............	1947	65	23·8	45	52·3	201	980·7034	0·0142	0·0073
262	(Queenville)...............	1947	65	28·7	45	52·3	408	·6857	·0160	·0021
263	(Long Creek)...............	1944	65	45·6	45	52·3	125	·7005	·0042	− ·0001
264	Maugerville................	1944	66	26·7	45	52·3	23	·6932	− ·0127	− ·0137
265	Long Creek................	1944	66	55·7	45	52·3	45	·6915	− ·0124	− ·0139
266	(Parkindale)...............	1947	65	03·4	45	52·4	433	·6903	·0228	·0081
267	Long Creek................	1944	65	46·4	45	52·6	25	·7056	− ·0005	− ·0014
268	Albert Mines...............	1947	64	40·1	45	52·7	241	·7039	·0179	·0097
269	(Pollett River).............	1947	65	04·4	45	52·7	356	·6950	·0198	·0077
270	(Pollett River).............	1947	65	06·2	45	52·7	297	·6985	·0177	·0076
271	(Maugerville)..............	1944	66	29·2	45	52·7	20	980·6912	−0·0156	−0·0163
272	(Irving)...................	1947	64	46·5	45	52·8	360	·7047	·0298	·0175
273	(Parkindale)...............	1947	64	59·5	45	52·8	508	·6887	·0277	·0104
274	(Anagance)................	1944	65	16·2	45	52·8	180	·7030	·0111	·0050
275	(Pollett River).............	1947	65	04·9	45	52·9	309	·6979	·0180	·0074
276	(Anagance Ridge)...........	1947	65	20·2	45	52·9	369	·6932	·0189	·0064
277	(Edgett's Landing)..........	1944	64	36·9	45	53·0	75	·7150	·0130	·0104
278	(Berryton)................	1947	64	52·3	45	53·0	345	·7000	·0233	·0116
279	(Cornhill).................	1947	65	21·0	45	53·0	236	·7019	·0150	·0069
280	Queenville.................	1947	65	29·5	45	53·0	470	·6797	·0148	− ·0013
281	(Dorchester)...............	1944	64	30·0	45	53·1	125	980·6898	−0·0077	−0·0120
282	(Anagance)................	1947	65	16·8	45	53·1	289	·6977	·0156	·0057
283	Head of Millstream..........	1947	65	31·8	45	53·1	252	·6921	·0065	− ·0021
284	(Maugerville)..............	1944	66	24·2	45	53·1	25	·6949	− ·0120	− ·0129
285	(Albert Mines).............	1947	64	39·3	45	53·2	415	·6895	·0191	·0050
286	Irving.....................	1947	64	48·5	45	53·2	551	·6905	·0329	·0142
287	(Pollett River).............	1947	65	05·5	45	53·2	233	·7029	·0154	·0075
288	Anagance Ridge............	1947	65	19·0	45	53·2	569	·6818	·0259	·0065
289	(White Mountain)...........	1947	65	25·7	45	53·2	644	·6741	·0253	·0033
290	Sheffield Church Monument..	1944	66	21·2	45	53·2	20	·6970	− ·0105	− ·0112
291	Beaumont..................	1944	64	35·2	45	53·3	30	980·7167	0·0099	0·0089
292	Berryton..................	1947	64	52·7	45	53·3	337	·6999	·0220	·0105
293	Pollett River..............	1947	65	05·9	45	53·3	219	·7040	·0150	·0075
294	(Parkindale)...............	1947	64	58·7	45	53·4	434	·6935	·0246	·0098
295	(Anagance Corner)..........	1944	65	13·5	45	53·4	132	·7063	·0090	·0045
296	(Cornhill East).............	1944	65	19·0	45	53·4	540	·6822	·0233	·0049
297	(Cornhill).................	1947	65	21·8	45	53·4	225	·7027	·0141	·0065
298	Sheffield..................	1944	66	17·9	45	53·4	20	·6971	− ·0107	− ·0114
299	Upper Maugerville..........	1944	66	31·8	45	53·4	30	·6927	− ·0142	− ·0152
300	(Edgett's Landing)..........	1944	64	37·7	45	53·5	140	·7067	·0100	·0052

PRINCIPAL FACTS FOR GRAVITY STATIONS—NEW BRUNSWICK—*Continued*

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name								Free Air	Bouguer
			°	′	°	′	Ft.			
301	(Shenstone)................	1947	64	44·6	45	53·5	225	980·7105	0·0218	0·0141
302	(Cornhill East).............	1944	65	17·2	45	53·6	447	·6880	·0199	·0047
303	(Pollett River).............	1947	65	06·0	45	53·7	236	·7036	·0156	·0076
304	(Hillsborough).............	1947	64	39·7	45	53·8	198	·7038	·0121	·0054
305	(Irving)....................	1947	64	46·1	45	53·8	328	·7031	·0236	·0125
306	(Long Creek)..............	1944	65	47·3	45	53·8	1,051	·7005	·0001	− ·0035
307	Sackville...................	1944	64	22·2	45	53·9	43	·6918	− ·0147	− ·0161
308	(Hillsborough).............	1947	64	40·7	45	53·9	299	·6996	·0172	·0070
309	(Berryton).................	1947	64	52·7	45	53·9	356	·6986	·0216	·0095
310	(Knightville)...............	1947	65	22·7	45	53·9	240	·7013	·0134	·0052
311	(Head of Millstream)........	1947	65	30·4	45	53·9	287	980·6911	0·0076	−0·0022
312	Pointe-de-Bute.............	1944	64	14·6	45	54·0	72	·6821	− ·0217	− ·0242
313	(Beaumont).................	1944	64	35·6	45	54·1	24	·7130	·0045	·0036
314	(Parkindale)................	1947	64	58·7	45	54·1	345	·6989	·0205	·0088
315	(Pollett River).............	1947	65	05·8	45	54·1	245	·7041	·0163	·0080
316	(Cornhill East).............	1944	65	17·4	45	54·1	255	·7008	·0140	·0053
317	(Cornhill East).............	1944	65	19·4	45	54·1	413	·6893	·0173	·0033
318	(Edgett's Landing)..........	1944	64	37·8	45	54·2	70	·7106	·0063	·0039
319	Isiah Corners..............	1947	64	42·9	45	54·2	226	·7069	·0173	·0096
320	(Irving)....................	1947	64	48·0	45	54·2	635	·6917	·0405	·0189
321	(Hillsborough).............	1947	64	40·3	45	54·3	85	980·7125	0·0094	0·0065
322	Irving......................	1947	64	47·4	45	54·3	545	·6895	·0297	·0111
323	(Pollett River).............	1947	65	06·0	45	54·3	319	·7000	·0189	·0080
324	(Pollett River).............	1947	65	05·2	45	54·4	149	·7105	·0133	·0082
325	(Hillsborough).............	1947	64	39·8	45	54·5	41	·7135	·0060	·0046
326	(Irving)....................	1947	64	46·7	45	54·5	522	·6907	·0284	·0106
327	(Pollett River).............	1947	65	06·2	45	54·5	349	·6989	·0203	·0084
328	(Shenstone)................	1947	64	45·0	45	54·6	444	·6947	·0250	·0098
329	(Hopper)...................	1947	64	58·8	45	54·6	336	·6994	·0195	·0081
330	Cornhill....................	1947	65	20·8	45	54·6	300	·6988	·0155	·0053
331	Salem......................	1947	64	42·5	45	54·7	133	980·7116	0·0124	0·0079
332	(Pollett River).............	1947	65	06·7	45	54·7	364	·6979	·0204	·0080
333	(Cornhill East).............	1944	65	17·6	45	54·7	210	·7023	·0104	·0032
334	Perry Settlement...........	1947	65	26·8	45	54·7	438	·6835	·0130	− ·0019
335	(Barker)....................	1944	66	33·7	45	54·7	30	·6927	− ·0162	− ·0172
336	Surrey......................	1944	64	38·4	45	54·8	66	·7114	·0058	·0036
337	(Steeves Mills).............	1947	64	47·7	45	54·8	427	·6957	·0241	·0095
338	(Petitcodiac)...............	1944	65	12·0	45	54·8	97	·7114	·0087	·0054
339	(Cornhill East).............	1944	65	19·6	45	54·8	480	·6861	·0194	·0031
340	(Berryton).................	1947	64	52·9	45	54·9	343	·6994	·0197	·0080
341	(Pollett River).............	1947	65	04·8	45	54·9	172	980·7096	0·0138	0·0079
342	(Petitcodiac)...............	1947	65	07·2	45	54·9	299	·7023	·0184	·0082
343	Rosborough................	1945	67	02·4	45	54·9	85	·6755	− ·0285	− ·0314
344	(Hopper)...................	1947	64	59·1	45	55·0	225	·7066	·0157	·0080
345	Boudreau Village...........	1944	64	36·3	45	55·1	98	·7076	·0045	·0012
346	(Salem)....................	1947	64	43·2	45	55·1	217	·7071	·0152	·0078
347	(Cornhill East).............	1944	65	17·8	45	55·1	373	·6931	·0159	·0032
348	(Pointe-de-Bute)...........	1947	64	15·4	45	55·2	26	·6870	− ·0230	− ·0238
349	(Petitcodiac)...............	1947	65	08·2	45	55·2	266	·7044	·0170	·0080
350	(Cornhill)..................	1947	65	22·7	45	55·2	453	·6884	·0186	·0031

PRINCIPAL FACTS FOR GRAVITY STATIONS—NEW BRUNSWICK—*Continued*

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name								Free Air	Bouguer
			°	′	°	′	Ft.			
351	(Dorchester)	1944	64	31·0	45	55·3	62	980·6973	−0·0095	−0·0116
352	(Hillsborough)	1944	64	41·5	45	55·3	180	·7061	·0104	·0048
353	(Berryton)	1947	64	53·1	45	55·3	328	·7006	·0186	·0072
354	(The Glades)	1947	65	04·7	45	55·3	267	·7048	·0173	·0082
355	(Lakeville)	1944	66	15·5	45	55·3	95	·6955	− ·0082	− ·0114
356	(Petitcodiac)	1947	65	14·2	45	55·4	270	·7017	·0144	·0052
357	Dubuc Settlement	1947	65	29·1	45	55·4	402	·6868	·0199	− ·0018
358	Hillsborough	1944	64	39·0	45	55·5	90	·7096	·0052	·0021
359	(Petitcodiac)	1947	65	10·0	45	55·5	209	·7077	·0145	·0073
360	(Petitcodiac)	1947	65	15·1	45	55·5	183	·7084	·0127	·0065
361	(Cornhill East)	1944	65	18·2	45	55·5	432	980·6903	0·0180	0·0033
362	Coles Island	1944	65	48·6	45	55·5	97	·7009	− ·0029	− ·0062
363	(Hillsborough)	1944	64	40·3	45	55·6	190	·7033	·0082	·0017
364	(Hopper)	1947	64	59·0	45	55·6	197	·7091	·0146	·0079
365	(South Devon)	1947	66	35·9	45	55·6	27	·6929	− ·0176	− ·0185
366	(The Glades)	1947	65	04·8	45	55·7	224	·7081	·0160	·0083
367	(Petitcodiac)	1947	65	09·7	45	55·7	174	·7098	·0130	·0070
368	(Steeves Mills)	1947	64	49·7	45	55·8	471	·6907	·0217	·0057
369	(Turtle Creek)	1947	64	53·0	45	55·8	309	·7016	·0174	·0068
370	Steeves Mills	1947	64	48·2	45	55·9	374	·6976	·0193	·0065
371	Petitcodiac	1947	65	10·6	45	55·9	97	980·7138	0·0094	0·0061
372	(Boudreau Village)	1944	64	36·7	45	56·0	40	·7128	·0030	·0016
373	(Hillsborough)	1944	64	39·4	45	56·0	26	·7115	·0003	− ·0005
374	(Lower Ridge)	1947	65	22·9	45	56·0	637	·6761	·0224	·0007
375	(Salem Station)	1944	64	42·2	45	56·1	112	·7119	·0086	·0048
376	(Perry Settlement)	1947	65	25·8	45	56·1	579	·6761	·0168	− ·0029
377	(Hillsborough)	1944	64	39·7	45	56·2	113	·7052	·0019	− ·0021
378	(Petitcodiac)	1944	65	10·8	45	56·2	83	·7146	·0085	·0057
379	Glenvale	1947	65	14·9	45	56·2	227	·7069	·0143	·0066
380	(Cornhill East)	1944	65	18·5	45	56·2	278	·7012	·0134	·0040
381	(Jolicure)	1947	64	12·5	45	56·3	49	980·6881	−0·0214	−0·0231
382	Upper Sackville	1945	64	20·6	45	56·3	34	·6944	− ·0165	− ·0177
383	Gray Island	1944	64	38·7	45	56·3	53	·7077	− ·0014	− ·0032
384	Steeves Mills	1947	64	47·4	45	56·3	529	·6881	·0238	·0057
385	(Turtle Creek)	1947	64	53·0	45	56·3	275	·7037	·0155	·0061
386	(Hopper)	1947	64	58·8	45	56·3	185	·7108	·0141	·0078
387	Fredericton	1947	66	38·4	45	56·4	33	·6945	·0166	− ·0178
388	(Pré d'en haut)	1944	64	37·3	45	56·5	82	·7093	·0026	− ·0002
389	(Weldon)	1944	64	40·0	45	56·5	113	·7057	·0019	− ·0019
390	(The Glades)	1947	65	04·7	45	56·5	139	·7139	·0126	·0078
391	(Young Cove Road)	1944	65	52·8	45	56·5	202	980·6944	−0·0010	−0·0079
392	(Weldon)	1944	64	41·9	45	56·6	72	·7151	·0074	·0049
393	(Turtle Creek)	1947	64	53·1	45	56·6	279	·7037	·0154	·0059
394	(Petitcodiac)	1947	65	12·0	45	56·6	145	·7123	·0114	·0065
395	(Young Cove)	1944	65	54·5	45	56·6	153	·6981	− ·0020	− ·0072
396	Jolicure	1944	64	13·0	45	56·7	45	·6847	− ·0258	− ·0273
397	(Hiram)	1947	64	43·1	45	56·7	187	·7088	·0117	·0053
398	Dawson	1947	64	47·2	45	56·7	540	·6877	·0238	·0054
399	Young Cove Road	1944	65	51·5	45	56·7	199	·6941	− ·0019	− ·0087
400	Weldon	1944	64	40·4	45	56·8	28	·7139	·0017	·0008

PRINCIPAL FACTS FOR GRAVITY STATIONS—NEW BRUNSWICK—*Continued*

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name								Free Air	Bouguer
			°	′	°	′	Ft.			
401	Hiram	1947	64	44·8	45	56·8	392	980·6957	0·0178	0·0044
402	Belliveau Village	1944	64	36·3	45	56·9	117	·7084	·0044	·0004
403	(Pré d'en haut)	1944	64	37·7	45	56·9	107	·7065	·0016	— ·0021
404	(Hopper)	1947	64	58·9	45	56·9	341	·7024	·0195	·0079
405	Young Cove	1944	65	56·0	45	56·9	57	·7047	— ·0049	— ·0069
406	Fredericton	1950	66	38·6	45	56·9	129	·6890	— ·0139	— ·0183
407	(Baltimore Station)	1947	64	50·3	45	57·0	343	·7000	·0172	·0055
408	(Turtle Creek)	1947	64	53·2	45	57·0	263	·7054	·0150	·0061
409	(Cornhill East)	1944	65	18·9	45	57·0	470	·6887	·0178	·0018
410	(Jolicure)	1947	64	13·8	45	57·1	31	·6947	— ·0177	— ·0187
411	Baltimore Station	1947	64	48·5	45	57·1	428	980·6946	0·0196	0·0050
412	Nixon	1947	64	56·3	45	57·1	356	·7004	·0186	·0065
413	(Hopper)	1947	64	58·8	45	57·1	332	·7032	·0191	·0078
414	(Lower Ridge)	1947	65	23·0	45	57·1	532	·6819	·0166	— ·0015
415	(Hiram)	1947	64	44·9	45	57·2	383	·6967	·0173	·0043
416	(Belliveau Village)	1944	64	36·1	45	57·3	215	·7037	·0083	·0010
417	(Pré d'en haut)	1944	64	37·9	45	57·3	30	·7123	— ·0005	— ·0015
418	(Weldon)	1944	64	40·5	45	57·3	118	·7094	·0049	·0009
419	(Turtle Creek)	1947	64	53·4	45	57·3	241	·7071	·0142	·0060
420	(Nixon)	1947	64	58·6	45	57·3	329	·7038	·0191	·0079
421	(Upper Dorchester)	1944	64	32·3	45	57·4	19	980·7131	—0·0008	—0·0015
422	(Weldon)	1944	64	41·0	45	57·4	103	·7137	·0077	·0042
423	(The Glades)	1947	65	04·7	45	57·4	122	·7158	·0116	·0074
424	(Ripples)	1944	66	13·8	45	57·4	85	·6980	— ·0097	— ·0126
425	Allandale Station	1945	67	17·8	45	57·5	295	·6517	— ·0365	— ·0465
426	Stony Creek Station	1947	64	45·1	45	57·6	337	·7006	·0163	·0048
427	Moncton Road Station	1947	64	47·3	45	57·6	425	·6961	·0201	·0056
428	Pré d'en haut	1944	64	38·0	45	57·7	129	·7092	·0051	·0007
429	(Stony Creek Station)	1947	64	45·2	45	57·7	408	·6962	·0184	·0045
430	(The Glades)	1947	65	03·6	45	57·7	219	·7102	·0146	·0071
431	Intervale	1947	65	11·9	45	57·7	120	980·7159	0·0110	0·0069
432	Hawkshaw	1944	67	15·0	45	57·7	130	·6628	— ·0412	— ·0456
433	(Pré d'en haut)	1944	64	37·5	45	57·8	205	·7048	·0078	·0008
434	Turtle Creek	1947	64	53·2	45	57·8	243	·7083	·0149	·0066
435	Nixon	1947	64	57·5	45	57·8	266	·7085	·0172	·0082
436	Middlesex	1947	65	01·8	45	57·8	317	·7043	·0178	·0070
437	Lower Ridge	1947	65	23·0	45	57·8	420	·6888	·0120	— ·0024
438	(Brooklyn Road)	1947	64	17·4	45	57·9	39	·7004	— ·0124	— ·0138
439	(Pré d'en haut)	1944	64	38·6	45	57·9	27	·7165	·0025	·0016
440	(River Glade)	1944	65	09·1	45	57·9	107	·7158	·0094	·0057
441	Hawkshaw	1947	67	13·0	45	57·9	126	980·6615	—0·0432	—0·0474
442	(Belliveau Village)	1944	64	36·0	45	58·0	180	·7084	·0087	·0026
443	(Turtle Creek)	1947	64	54·9	45	58·0	303	·7051	·0170	·0067
444	(South Devon)	1944	66	36·4	45	58·0	50	·6939	— ·0180	— ·0197
445	(Intervale)	1947	65	13·6	45	58·1	132	·7115	·0071	·0026
446	Kinnear Settlement	1947	65	15·4	45	58·1	258	·7053	·0128	·0040
447	(Havelock)	1947	65	19·1	45	58·1	366	·6952	·0128	·0004
448	(Stony Creek Station)	1947	64	45·3	45	58·1	357	·7004	·0172	·0050
449	(Nixon)	1947	64	57·3	45	58·1	246	·7105	·0168	·0085
450	(Nixon)	1947	64	59·1	45	58·1	287	·7077	·0179	·0081

PRINCIPAL FACTS FOR GRAVITY STATIONS—NEW BRUNSWICK—*Continued*

Station		Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name							Free Air	Bouguer
		°	′	°	′	Ft.			
451	(Weldon) 1944	64	41·4	45	58·2	210	980·7081	0·0110	0·0038
452	(Thornbrook) 1947	65	23·2	45	58·2	437	·6880	·0122	− ·0027
453	Gautreau Village 1944	64	39·0	45	58·3	138	·7116	·0075	·0028
454	(Moncton Road Station) 1947	64	47·2	45	58·3	410	·6979	·0194	·0054
455	(Turtle Creek) 1947	64	53·6	45	58·3	187	·7116	·0121	·0057
456	Middlesex 1947	65	00·5	45	58·3	265	·7087	·0165	·0075
457	(Jolicure) 1947	64	13·0	45	58·4	41	·7013	− ·0120	− ·0134
458	Brooklyn Road 1947	64	17·5	45	58·4	62	·7013	− ·0101	− ·0122
459	(Nixon) 1947	64	57·7	45	58·4	182	·7148	·0147	·0085
460	(River Glade) 1947	65	04·9	45	58·4	99	·7183	·0104	·0070
461	(Young Cove) 1944	65	55·3	45	58·4	145	980·7030	−0·0006	−0·0055
462	(Stony Creek Station) 1947	64	44·7	45	58·5	168	·7129	·0113	−1·0056
463	(Turtle Creek) 1947	64	53·7	45	58·5	226	·7101	·0140	·0063
464	(River Glade) 1947	65	05·5	45	58·5	111	·7173	·0103	·0066
465	(Fawcett) 1947	65	11·5	45	58·5	141	·7157	·0116	·0068
466	St. Joseph 1944	64	34·0	45	58·6	72	·7157	·0050	·0025
467	(Kinnear Settlement) 1947	65	16·7	45	58·6	486	·6911	·0193	·0028
468	Meductic 1944	67	29·1	45	58·6	147	·6852	− ·0185	− ·0235
469	College Bridge 1950	64	33·0	45	58·7	28	·7187	·0037	1·0027
470	(River Glade) 1947	65	06·5	45	58·7	67	·7195	·0081	·0058
471	Marysville 1944	66	35·6	45	58·7	50	980·6962	−0·0168	−0·0185
472	(Colpitts) 1947	64	58·0	45	58·9	173	·7152	·0135	·0076
473	(Stony Creek) 1944	64	41·8	45	59·0	165	·7133	·0107	·0051
474	Colpitts 1947	64	58·2	45	59·0	100	·7193	·0106	·0072
475	(Middlesex) 1947	65	00·9	45	59·0	138	·7171	·0120	·0073
476	(Stony Creek) 1947	64	44·4	45	59·1	358	·7017	·0171	·0049
477	(Turtle Creek) 1947	64	53·9	45	59·1	238	·7119	·0160	·0079
478	(Colpitts) 1947	64	58·4	45	59·1	103	·7195	·0109	·0074
479	(Gautreau Village) 1944	64	40·1	45	59·2	34	·7227	·0075	·0063
480	(Moncton Road Station) 1947	64	46·3	45	59·2	345	·7034	·0174	·0057
481	(River Glade) 1947	65	07·1	45	59·2	91	980·7186	0·0088	0·0057
482	(Havelock) 1947	65	17·6	45	59·2	408	·6945	·0145	·0006
483	River Glade 1944	65	07·1	45	59·3	89	·7184	·0082	·0051
484	(Havelock) 1947	65	19·5	45	59·3	276	·7005	·0079	− ·0015
485	(Ripples) 1944	66	12·1	45	59·3	210	·6923	− ·0065	− ·0137
486	Fawcett Hill 1947	65	13·2	45	59·4	270	·7066	·0132	·0040
487	(Havelock) 1947	65	21·9	45	59·4	396	·6936	·0120	− ·0014
488	(Stony Creek) 1947	64	44·4	45	59·5	392	·7009	·0189	·0055
489	(River Glade) 1947	65	08·3	45	59·5	153	·7158	·0113	·0061
490	Fawcett 1947	65	12·1	45	59·5	141	·7166	·0110	·0062
491	(Baie-Verte) 1944	64	08·4	45	59·6	80	980·6993	−0·0122	−0·0148
492	(Dover) 1944	64	41·2	45	59·6	30	·7241	·0079	·0069
493	Stony Creek 1944	64	42·5	45	59·6	66	·7219	·0091	·0069
494	(Turtle Creek) 1947	64	54·2	45	59·6	193	·7160	·0151	·0086
495	(Crossman) 1947	64	45·3	45	59·7	355	·7033	·0175	·0054
496	(Colpitts) 1947	64	58·4	45	59·7	148	·7176	·0123	·0073
497	(Crossman) 1947	64	45·1	45	59·8	384	·7033	·0201	·0054
498	(Jolicure) 1947	64	14·3	45	59·9	60	·7055	− ·0084	− ·0104
499	Memramcook W. 1944	64	34·3	45	59·9	29	·7229	·0061	·0051
500	(Crossman) 1947	64	45·0	45	59·9	366	·7024	·0173	·0049

PRINCIPAL FACTS FOR GRAVITY STATIONS—NEW BRUNSWICK—*Continued*

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name		°	′	°	′	Ft.		Free Air	Bouguer
501	(Middlesex)	1947	65	01·4	45	59·9	76	980·7214	0·0091	0·0073
502	(River Glade)	1947	65	09·3	45	59·9	143	·7173	·0112	·0064
503	Havelock	1944	65	19·1	45	59·9	295	·7004	·0086	− ·0014
504										
505	(Midgic)	1945	64	18·1	46	00·0	26	·7103	− ·0070	− ·0078
506	(Coverdale)	1947	64	58·7	46	00·0	136	·7186	·0117	·0071
507	(Killams Mills)	1947	65	12·5	46	00·0	195	·7130	·0116	·0050
508	(Killams Mills)	1947	65	14·4	46	00·1	381	·6987	·0147	·0018
509	(Killams Mills)	1947	65	16·0	46	00·1	430	·6942	·0149	·0002
510	(Granville)	1944	65	54·4	46	00·1	61	·7105	− ·0036	− ·0056
511	Dover	1944	64	41·5	46	00·2	44	980·7246	0·0087	0·0072
512	(Coverdale)	1947	64	54·1	46	00·2	165	·7194	·0149	·0093
513	(Killams Mills)	1947	65	12·7	46	00·2	219	·7116	·0113	·0041
514	Memramcook	1944	64	33·1	46	00·3	73	·7197	·0065	·0040
515	(Memramcook W.)	1944	64	37·5	46	00·4	386	·7036	·0196	·0065
516	(Stony Creek)	1944	64	42·5	46	00·4	195	·7162	·0142	·0076
517	(Crossman)	1947	64	45·2	46	00·4	307	·7086	·0172	·0067
518	(Coverdale)	1947	64	52·9	46	00·4	209	·7175	·0169	·0097
519	(Salisbury)	1947	65	06·6	46	00·4	130	·7177	·0096	·0052
520	(Killams Mills)	1947	65	12·8	46	00·4	239	·7090	·0112	·0030
521	(Havelock)	1947	65	22·3	46	00·4	440	980·6936	0·0147	−0·0014
522	(Salisbury)	1944	65	04·5	46	00·5	54	·7223	·0070	·0051
523	Keswick	1950	66	49·9	46	00·5	36	·7017	− ·0153	− ·0166
524	(Coverdale)	1947	64	59·2	46	00·6	79	·7220	·0088	·0061
525	(Killams Mills)	1947	65	15·0	46	00·6	378	·6976	·0125	− ·0003
526	(Havelock)	1947	65	17·7	46	00·6	310	·7006	·0092	− ·0014
527	Penniac Bridge	1944	66	34·7	46	00·6	43	·7001	− ·0165	− ·0179
528	(Coverdale)	1947	64	54·2	46	00·7	113	·7228	·0126	·0088
529	(Salisbury)	1944	65	10·9	46	00·8	273	·7089	·0137	·0044
530	Coverdale	1947	64	58·2	46	00·9	101	·7214	·0098	·0064
531	(Salisbury)	1947	65	00·1	46	00·9	80	980·7230	0·0094	0·0067
532	Pine Glen School	1947	64	45·6	46	01·0	262	·7137	·0171	·0082
533	(Coverdale)	1947	64	59·7	46	01·0	91	·7221	·0095	·0064
534	(Havelock)	1947	65	20·6	46	01·0	368	·7009	·0143	·0018
535	(Cookville)	1945	64	22·2	46	01·1	217	·7078	·0069	− ·0005
536	(Coverdale)	1947	64	52·2	46	01·1	155	·7215	·0148	·0095
537	(Salisbury)	1947	65	02·1	46	01·1	51	·7243	·0078	·0061
538	Killams Mills	1947	65	13·6	46	01·1	248	·7067	·0087	·0003
539	(Salisbury)	1947	65	06·9	46	01·2	198	·7136	·0107	·0040
540	(Salisbury)	1947	65	09·2	46	01·2	258	·7101	·0129	·0041
541	(Upper Dover)	1944	64	41·2	46	01·3	47	980·7271	0·0099	0·0083
542	(Lower Coverdale)	1944	64	42·7	46	01·3	145	·7219	·0139	·0090
543	(Steeves Settlement)	1947	65	18·3	46	01·3	212	·7090	·0073	·0001
544	(Albright)	1944	66	11·4	46	01·3	206	·6959	− ·0063	− ·0133
545	(Salisbury)	1947	65	05·7	46	01·4	179	·7152	·0102	·0041
546	(Havelock)	1947	65	16·4	46	01·4	322	·7012	·0097	− ·0013
547	(Salisbury)	1944	65	11·3	46	01·5	296	·7061	·0120	·0020
548	Royal Road	1945	66	42·0	46	01·5	127	·7006	− ·0094	− ·0137
549	(Gayton)	1944	64	34·6	46	01·6	111	·7237	·0120	·0083
550	Crossman Church	1947	64	46·3	46	01·6	223	·7168	·0157	·0081

PRINCIPAL FACTS FOR GRAVITY STATIONS—NEW BRUNSWICK—*Continued*

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name		°	′	°	′	Ft.		Free Air	Bouguer
551	Mud Creek	1947	64	44·5	46	01·7	216	980·7181	0·0162	0·0089
552	Salisbury	1947	65	02·3	46	01·7	70	·7233	·0077	·0053
553	Salisbury	1944	65	02·3	46	01·7	77	·7232	·0082	·0056
554	(Salisbury)	1944	65	06·5	46	01·7	194	·7133	·0093	·0027
555	(Middle Coverdale)	1947	64	48·4	46	01·8	189	·7200	·0154	·0089
556	(Salisbury)	1947	65	07·8	46	01·8	243	·7124	·0129	·0046
557	(Havelock)	1947	65	22·9	46	01·8	243	·7129	·0134	·0051
558	Granville	1944	65	52·9	46	01·8	53	·7134	− ·0040	− ·0058
559	(Coverdale)	1947	64	51·9	46	01·9	133	·7232	·0131	·0086
560	Lower Coverdale	1944	64	43·1	46	02·0	180	·7224	·0166	·0105
561	(Salisbury)	1947	65	08·7	46	02·0	175	980·7155	0·0093	0·0033
562	Penniac	1944	66	34·5	46	02·0	60	·7041	− ·0130	− ·0150
563	Gayton	1944	64	33·6	46	02·1	37	·7288	·0095	·0082
564	Smith Lake	1944	64	38·5	46	02·1	275	·7145	·0176	·0082
565	(Salisbury)	1947	65	06·6	46	02·2	253	·7110	·0118	·0032
566	(Killams Mills)	1947	65	13·3	46	02·2	236	·7087	·0079	− ·0001
567	(Killams Mills)	1947	65	14·5	46	02·2	299	·7048	·0099	− ·0003
568	(Havelock)	1947	65	20·9	46	02·2	258	·7103	·0116	·0028
569	(Salisbury)	1944	65	11·5	46	02·3	350	·7014	·0111	− ·0008
570	(Mill Creek)	1947	64	47·1	46	02·3	192	·7193	·0142	·0076
571	Upper Dover	1944	64	41·5	46	02·3	113	980·7253	0·0127	0·0089
572	(Havelock)	1947	65	24·9	46	02·3	203	·7159	·0118	·0049
573	(Coverdale)	1947	64	54·7	46	02·4	108	·7231	·0100	·0063
574	(Salisbury)	1947	65	03·0	46	02·4	157	·7183	·0098	·0044
575	Cumberland Bay	1944	65	52·5	46	02·4	36	·7154	− ·0045	− ·0057
576	(Salisbury)	1947	65	05·8	46	02·5	276	·7103	·0128	·0034
577	Mill Creek	1947	64	47·2	46	02·6	111	·7258	·0126	·0089
578	Howard Brook	1944	66	08·1	46	02·6	223	·6977	− ·0049	− ·0125
579	(Lower Coverdale)	1944	64	43·5	46	02·7	95	·7286	·0138	·0106
580	(Salisbury)	1944	65	09·6	46	02·7	327	·7044	·0115	·0003
581	(Middle Coverdale)	1947	64	48·9	46	02·8	139	980·7245	0·0137	0·0089
582	Coverdale	1947	64	52·0	46	02·8	73	·7272	·0102	·0077
583	(Coverdale)	1947	64	54·5	46	02·8	66	·7260	·0083	·0061
584	Upper Coverdale	1947	64	57·9	46	02·8	107	·7232	·0094	·0057
585	(Salisbury)	1947	65	05·1	46	02·8	276	·7111	·0132	·0038
586	(Killams Mills)	1947	65	15·6	46	02·8	301	·7052	·0096	− ·0006
587	(Gayton)	1944	64	34·9	46	02·9	210	·7203	·0161	·0089
588	(Salisbury)	1947	65	07·5	46	02·9	169	·7139	·0058	·0000
589	(Killams Mills)	1947	65	09·0	46	02·9	267	·7094	·0105	·0014
590	(Salisbury)	1944	65	12·2	46	02·9	357	·7017	·0113	− ·0009
591	(Killams Mills)	1947	65	13·7	46	02·9	285	980·7073	0·0101	0·0004
592	Port Elgin	1944	64	05·4	46	03·1	6	·7160	− ·0077	− ·0079
593	(Gunningsville)	1947	64	47·3	46	03·1	123	·7257	·0130	·0088
594	(Boundary Creek)	1944	65	00·1	46	03·1	96	·7232	·0079	·0047
595	(Salisbury)	1947	65	03·7	46	03·1	238	·7136	·0117	·0036
596	(Havelock)	1947	65	27·1	46	03·1	196	·7171	·0112	·0046
597	(Havelock)	1947	65	21·2	46	03·2	149	·7206	·0101	·0050
598	(Upper Dover)	1944	64	41·0	46	03·3	174	·7222	·0140	·0080
599	(Salisbury)	1944	65	10·3	46	03·3	365	·7023	·0120	− ·0004
600	(Lower Coverdale)	1944	64	43·9	46	03·4	75	·7297	·0120	·0094

PRINCIPAL FACTS FOR GRAVITY STATIONS—NEW BRUNSWICK—*Continued*

Station			Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies	
No.	Name						Free Air	Bouguer
			° ′	° ′	Ft.			
601	(Salisbury)................	1944	65 05·9	46 03·4	170	980·7157	0·0069	0·0011
602	(Boundary Creek)..........	1944	64 57·5	46 03·4	65	·7258	·0071	·0049
603	(Salisbury)................	1944	65 04·1	46 03·4	225	·7148	·0112	·0035
604	(Salisbury)................	1947	65 04·1	46 03·4	225	·7151	·0115	·0038
605	(Salisbury)................	1947	65 05·9	46 03·4	170	·7157	·0069	·0011
606	Middle Coverdale..........	1947	64 49·2	46 03·6	104	·7269	·0116	·0080
607	New Zion..................	1944	66 05·7	46 03·6	201	·7038	−·0024	−·0092
608	Fox Creek.................	1944	64 42·3	46 03·8	26	·7322	·0092	·0084
609	Jones......................	1944	64 54·8	46 03·8	105	·7244	·0089	·0053
610	(Salisbury)................	1947	65 04·7	46 03·8	208	·7169	·0111	·0040
611	(Salisbury)................	1944	65 05·8	46 03·8	177	980·7148	0·0060	0·0000
612	(Havelock)................	1947	65 21·7	46 03·8	115	·7228	·0082	·0043
613	Zealand....................	1950	66 56·0	46 03·8	105	·6858	−·0297	−·0333
614	(Calhoun)..................	1944	64 35·2	46 03·9	210	·7218	·0161	·0089
615	(Salisbury)................	1947	65 07·6	46 03·9	231	·7130	·0092	·0014
616	(Bridgedale)...............	1944	64 44·7	46 04·0	75	·7334	·0148	·0122
617	(Salisbury)................	1947	65 08·9	46 04·0	320	·7068	·0112	·0003
618	....							
619	Killams Mills..............	1947	65 12·2	46 04·0	296	·7084	·0105	·0005
620	....							
621	(Killams Mills)............	1947	65 13·8	46 04·0	188	980·7141	0·0061	−0·0003
622	(Killams Mills)............	1947	65 15·7	46 04·0	282	·7080	·0088	−·0008
623	(Havelock)................	1947	65 17·0	46 04·0	223	·7133	·0086	·0010
624	(Havelock)................	1947	65 28·3	46 04·0	69	·7282	·0090	·0066
625	The Range..................	1944	65 54·1	46 04·0	47	·7137	−·0076	−·0092
626	(Penniac)..................	1944	66 35·4	46 04·0	73	·7083	−·0105	−·0130
627	(Centre Village)...........	1945	64 16·8	46 04·1	130	·7177	·0041	−·0003
628	(Gunningsville)............	1947	64 47·7	46 04·1	31	·7329	·0100	·0090
629	(Salisbury)................	1944	65 10·3	46 04·1	425	·7007	·0149	·0004
630	Calhoun....................	1944	64 34·2	46 04·2	50	·7316	·0103	·0086
631	(Havelock)................	1947	65 18·0	46 04·2	185	980·7186	0·0100	0·0037
632	(Havelock)................	1947	65 18·9	46 04·2	138	·7221	·0091	·0044
633	(Havelock)................	1947	65 21·9	46 04·2	65	·7262	·0063	·0041
634	St. Anselme................	1944	64 43·3	46 04·3	58	·7308	·0102	·0082
635	....							
636	(Havelock)................	1947	65 19·9	46 04·3	120	·7226	·0078	·0037
637	Hardy......................	1944	64 01·8	46 04·5	50	·7188	−·0029	−·0046
638	Bridgedale.................	1944	64 45·5	46 04·5	80	·7319	·0130	·0103
639	(Minto)....................	1944	66 03·4	46 04·5	102	·7110	−·0058	−·0093
640	(Nashwaak)................	1944	66 36·8	46 04·6	65	·7103	−·0102	−·0124
641	(Havelock)................	1947	65 25·2	46 04·8	62	980·7288	0·0077	0·0056
642	(Salisbury)................	1947	65 08·8	46 04·9	365	·7061	·0134	·0010
643	(Zealand)..................	1950	67 04·8	46 04·9	614	·6568	−·0125	−·0334
644	(Salisbury)................	1944	65 06·1	46 05·0	272	·7133	·0117	·0024
645	(Drisdelle)................	1945	64 23·7	46 05·1	130	·7268	·0117	·0073
646	Chartersville..............	1944	64 44·0	46 05·1	29	·7353	·0107	·0097
647	Moncton P.O................	1947	64 47·2	46 05·3	55	·7330	·0105	·0086
648	Woodside...................	1944	64 07·2	46 05·5	44	·7227	−·0011	−·0026
649	Melrose....................	1944	63 56·6	46 05·7	93	·7239	·0044	·0013
650	Léger Corner...............	1944	64 44·9	46 05·7	43	·7332	·0090	·0076

PRINCIPAL FACTS FOR GRAVITY STATIONS—NEW BRUNSWICK—*Continued*

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name								Free Air	Bouguer
			°	′	°	′	Ft.			
651	(Salisbury)	1944	65	06·4	46	05·8	355	980·7074	0·0124	0·0003
652	(Anderson)	1945	64	15·6	46	05·9	106	·7252	·0067	·0031
653	(Meadowbrook)	1944	64	35·3	46	05·9	83	·7350	·0143	·0115
654	Coal Creek	1944	65	53·0	46	06·0	64	·7119	– ·0107	– ·0129
655	(Moncton)	1944	64	48·7	46	06·1	115	·7295	·0115	·0076
656	Painsec	1944	64	38·5	46	06·2	218	·7254	·0169	·0095
657	Lakeburn	1944	64	41·0	46	06·2	209	·7248	·0155	·0083
658	(Minto)	1944	66	03·0	46	06·5	244	·7027	– ·0037	– ·0121
659	Malden	1944	63	52·9	46	06·6	90	·7244	·0033	·0002
660	(Nashwaak)	1944	66	37·1	46	06·6	72	·7136	– ·0092	– ·0117
661	(Hildegard)	1944	64	50·1	46	06·7	110	980·7306	0·0112	0·0075
662	Humphreys School	1947	64	46·5	46	06·9	64	·7340	·0099	·0077
663	(Salisbury)	1944	65	07·0	46	07·0	230	·7146	·0061	– ·0017
664	(Harrisville)	1944	64	43·1	46	07·1	183	·7279	·0147	·0085
665	Hamtown	1945	66	46·1	46	07·2	783	·6672	·0003	– ·0163
666	Hildegard	1944	64	51·3	46	07·4	150	·7286	·0120	·0069
667	Drisdelle	1944	64	23·4	46	07·7	88	·7344	·0115	·0085
668	Wilson Brook	1944	65	53·4	46	07·7	62	·7082	– ·0172	– ·0193
669	(Moncton)	1947	64	46·2	46	07·8	119	·7330	·0128	·0087
670	(Anderson)	1945	64	14·0	46	07·9	89	·7311	·0080	·0049
671	(Magnetic Hill)	1944	64	53·0	46	07·9	190	980·7254	0·0118	0·0053
672	(Shemogue)	1944	64	08·0	46	08·2	22	·7351	·0052	·0044
673	Scoudouc	1944	64	34·3	46	08·2	95	·7406	·0175	·0143
674	Lutz Mountain	1944	64	54·1	46	08·2	410	·7117	·0183	·0043
675	Durham	1944	66	36·6	46	08·2	78	·7131	– ·0116	– ·0142
676	Bayfield	1944	63	49·0	46	08·3	12	·7285	– ·0025	– ·0029
677	(Chapman)	1944	64	04·3	46	08·3	61	·7320	·0056	·0036
678	(St. André-de-Shediac)	1945	64	19·3	46	08·3	95	·7358	·0126	·0094
679	Millville	1950	67	11·2	46	08·3	477	·6759	– ·0113	– ·0276
680	Spencer	1944	63	52·8	46	08·7	15	·7360	·0047	·0042
681	(Lutz Mountain)	1944	64	55·3	46	08·7	410	980·7126	0·0185	0·0045
682	Shediac Road	1947	64	40·4	46	08·9	205	·7305	·0167	·0097
683										
684	Woodstock	1944	67	34·5	46	09·0	194	·7032	– ·0118	– ·0184
685	(Scoudouc Station)	1944	64	33·8	46	09·1	85	·7437	·0184	·0155
686	Woodstock	1950	67	34·0	46	09·2	190	·7032	– ·0124	– ·0189
687	Shemogue	1944	64	11·1	46	09·3	50	·7360	·0071	·0054
688	Upper Aboushagan	1944	64	24·2	46	09·3	131	·7387	·0174	·0130
689	(Chipman)	1944	65	53·6	46	09·3	70	·7072	– ·0198	– ·0222
690	(Hardwood Ridge)	1944	66	02·3	46	09·3	313	·6976	– ·0066	– ·0172
691	(Murray Corner)	1944	63	55·2	46	09·5	14	980·7404	0·0078	0·0073
692	(Irishtown Station)	1947	64	46·9	46	09·6	180	·7319	·0147	·0086
693	Indian Mountain	1944	64	56·2	46	09·7	472	·7081	·0183	·0022
694	(Stiles Village)	1944	64	52·8	46	09·8	585	·7046	·0251	·0052
695	Scoudouc Station	1944	64	33·7	46	10·0	101	·7474	·0222	·0188
696	(Shediac Road)	1944	64	39·0	46	10·2	189	·7346	·0174	·0109
697	Murray Corner	1944	63	57·6	46	10·3	15	·7417	·0080	·0075
698	Cormier Village	1944	64	21·1	46	10·3	63	·7429	·0137	·0116
699	(Shemogue)	1944	64	13·0	46	10·5	95	·7369	·0104	·0072
700	(Indian Mountain)	1944	64	56·9	46	10·5	330	·7145	·0101	– ·0011

PRINCIPAL FACTS FOR GRAVITY STATIONS—NEW BRUNSWICK—*Continued*

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name								Free Air	Bouguer
			°	′	°	′	Ft.			
701	St. André-de-Shediac........	1944	64	18·0	46	10·7	115	980·7395	0·0146	0·0107
702	(Ohio-du-Barachois)..........	1945	64	28·9	46	10·7	128	·7451	·0214	·0171
703	Grant......................	1944	64	01·6	46	10·8	15	·7418	·0073	·0068
704	(Chipman)..................	1944	65	53·5	46	10·9	45	·7131	·0187	·0202
705	(Hardwood Ridge)..........	1944	66	01·6	46	11·0	319	·6962	− ·0100	− ·0209
706	(Chipman)..................	1944	65	59·3	46	11·2	214	·7037	− ·0126	− ·0199
707	Irishtown Station...........	1947	64	47·6	46	11·3	233	·7294	·0146	·0067
708	(Gallagher).................	1944	64	58·3	46	11·4	280	·7170	·0065	− ·0030
709	Glaude.....................	1944	64	25·4	46	11·5	57	·7485	·0170	·0150
710	(Scoudouc Station)..........	1944	64	33·8	46	11·5	90	·7480	·0196	·0165
711	Botsford Portage............	1944	64	14·9	46	11·6	103	980·7410	0·0136	0·0101
712	(St. André-de-Shediac).......	1944	64	18·7	46	11·8	100	·7438	·0158	·0114
713	Taymouth..................	1944	66	36·2	46	11·8	142	·7124	− ·0116	− ·0165
714	(Chipman)..................	1944	65	56·3	46	12·0	123	·7113	− ·0148	− ·0190
715	(Moncton Road)............	1944	64	36·6	46	12·1	145	·7424	·0181	·0132
716	(North Tay)................	1945	66	47·9	46	12·2	467	·6973	·0032	− ·0127
717	(Irishtown)................	1947	64	48·2	46	12·6	319	·7314	·0228	·0119
718	(Irishtown)................	1947	64	49·5	46	12·6	459	·7228	·0274	·0117
719	Gallagher..................	1944	64	59·8	46	12·7	315	·7165	·0074	− ·0033
720	(Cape Bald)................	1944	64	17·9	46	12·8	26	·7524	·0159	·0151
721	Cape Bald..................	1944	64	16·3	46	12·9	59	980·7487	0·0151	0·0131
722	(Millville)..................	1950	67	16·0	46	13·0	530	·6984	·0091	− ·0090
723	Robichaud..................	1944	64	22·8	46	13·1	23	·7541	·0170	·0162
724	Chapmans Corner...........	1944	64	34·0	46	13·1	32	·7529	·0166	·0155
725	Dupuis Corner..............	1944	64	19·4	46	13·3	42	·7526	·0170	·0155
726	Shediac....................	1944	64	32·5	46	13·3	47	·7529	·0177	·0161
727	Barachois..................	1944	64	25·5	46	13·4	35	·7539	·0174	·0162
728	(Shediac)..................	1944	64	30·9	46	13·5	46	·7534	·0177	·0162
729	(Gilberts Corner)...........	1944	64	35·1	46	13·5	80	·7483	·0158	·0131
730	Boudreau...................	1944	64	29·0	46	13·6	49	·7542	·0187	·0170
731	(Barachois)................	1944	64	27·0	46	13·7	29	980·7555	0·0180	0·0170
732	(Gaspereau Forks)..........	1945	65	50·7	46	13·8	43	·7230	− ·0134	− ·0148
733	Gilberts Corner.............	1944	64	34·2	46	13·9	55	·7513	·0160	·0141
734	(Gallagher).................	1944	65	01·0	46	14·0	278	·7177	·0032	− ·0062
735	(McQuade)..................	1947	64	50·2	46	14·2	334	·7294	·0198	·0084
736	Pointe de Chene............	1944	64	31·4	46	14·3	3	·7564	·0155	·0154
737	Covered Bridge.............	1944	66	37·0	46	14·3	136	·7163	− ·0121	− ·0167
738	(Gilberts Corner)...........	1944	64	34·2	46	14·4	19	·7544	·0149	·0142
739	(Gilberts Corner)...........	1944	64	34·2	46	14·7	15	·7548	·0144	·0139
740	Canaan Station.............	1944	65	03·7	46	14·9	258	·7235	·0057	− ·0031
741	....	1947	64	51·0	46	15·4	154	980·7386	0·0103	0·0050
742	(Shediac Bridge)...........	1944	64	34·2	46	15·8	38	·7541	·0143	·0130
743	(Salmon River).............	1945	65	48·2	46	16·2	76	·7258	− ·0111	− ·0136
744	Hebert Siding..............	1944	65	05·0	46	16·5	282	·7299	·0119	·0023
745	Shediac Bridge.............	1944	64	34·8	46	16·9	9	·7561	·0118	·0115
746	Stanley....................	1945	66	43·8	46	17·2	288	·7136	− ·0048	− ·0146
747	(Hartland).................	1950	67	20·0	46	17·5	328	·7094	− ·0057	− ·0169
748	(Hebert Siding)............	1944	65	06·0	46	17·8	268	·7325	·0113	·0022
749	Grandigue.................	1944	64	33·8	46	18·0	51	·7573	·0154	·0137
750	Hartland...................	1950	67	31·0	46	18·0	169	·7199	− ·0109	− ·0167

PRINCIPAL FACTS FOR GRAVITY STATIONS—NEW BRUNSWICK—*Continued*

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name								Free Air	Bouguer
			°	′	°	′	Ft.			
751	(Salmon River).............	1945	65	41·5	46	18·1	102	980·7322	−0·0051	−0·0086
752	Hartland....................	1944	67	31·7	46	18·3	168	·7197	− ·0017	− ·0174
753	(Cocagne)..................	1944	64	35·8	46	18·4	86	·7562	·0170	·0141
754	Cross Creek................	1944	66	35·1	46	18·7	333	·7104	− ·0061	− ·0174
755	(St. Marcel)................	1944	64	34·3	46	18·8	81	·7574	·0171	·0144
756	Birch Siding................	1944	65	07·0	46	19·0	300	·7325	·0125	·0023
757	St. Marcel..................	1944	64	35·0	46	19·5	55	·7597	·0160	·0141
758	Cocagne.....................	1944	64	36·8	46	19·9	42	·7597	·0141	·0126
759	(Salmon River).............	1945	65	36·7	46	19·9	141	·7335	− ·0028	− ·0076
760	(Birch Siding)..............	1944	65	08·1	46	20·2	273	·7367	·0124	·0031
761	Cocagne P.O................	1944	64	37·3	46	20·5	9	980·7613	0·0116	0·0113
762	(Cocagne)..................	1944	64	37·8	46	21·1	56	·7581	·0120	·0101
763	(Napadogan)...............	1945	66	47·9	46	21·2	720	·6888	·0050	− ·0195
764	Coal Branch Station.........	1944	65	09·0	46	21·4	208	·7414	·0092	·0021
765	(McGivney).................	1944	66	33·4	46	21·4	552	·7072	·0073	− ·0115
766	(Salmon River).............	1945	65	30·6	46	21·8	85	·7401	− ·0039	− ·0072
767	Breau Village..............	1944	64	38·0	46	22·3	88	·7578	·0129	·0099
768	(Coal Branch Station).......	1944	65	10·1	46	22·6	235	·7343	·0028	− ·0052
769	(Clearwater)...............	1944	66	30·8	46	22·8	502	·7151	·0084	− ·0087
770	Stickney....................	1947	67	33·5	46	23·1	178	·7259	− ·0118	− ·0178
771	Adamsville.................	1944	65	11·2	46	23·9	297	980·7232	−0·0045	−0·0146
772	Déspres Village............	1944	64	39·6	46	24·0	92	·7599	·0129	·0099
773	Napadogan.................	1945	66	55·3	46	24·7	899	·6779	·0057	− ·0250
774	(Salmon River).............	1945	65	24·6	46	25·1	130	·7413	− ·0039	− ·0083
775	(Astle).....................	1944	66	28·8	46	25·1	512	·7174	·0082	− ·0093
776	Ward Corner...............	1944	64	40·7	46	25·2	86	·7656	·0162	·0133
777	Grangeville................	1944	65	12·3	46	25·3	215	·7286	− ·0088	− ·0161
778	Florenceville..............	1944	67	36·7	46	26·4	190	·7270	− ·0144	− ·0209
779	(Grangeville)..............	1944	65	13·4	46	26·5	173	·7363	− ·0069	− ·0128
780	St. François de Kent.........	1944	64	41·2	46	26·7	67	·7728	·0193	·0170
781	(Buctouche)...............	1945	64	41·6	46	27·4	35	980·7747	0·0171	0·0159
782	(Salmon River).............	1945	65	20·7	46	27·4	152	·7446	− ·0020	− ·0072
783	Boiestown..................	1944	66	24·8	46	27·5	236	·7387	− ·0001	− ·0081
784	(Buctouche)...............	1944	64	42·3	46	27·7	33	·7724	·0142	·0131
785	(Harcourt).................	1944	65	14·4	46	27·8	167	·7409	− ·0048	− ·0105
786	Bristol......................	1950	67	34·3	46	28·4	206	·7287	− ·0142	− ·0213
787	(Buctouche)...............	1944	64	43·5	46	29·1	38	·7657	·0059	·0046
788	Glassville..................	1950	67	25·0	46	29·2	755	·6850	− ·0076	− ·0333
789	(Mortimer).................	1944	65	15·3	46	29·3	155	·7470	− ·0022	− ·0075
790	Ludlow.....................	1944	66	20·5	46	29·6	190	·7449	− ·0014	− ·0079
791	(Buctouche)...............	1944	64	44·2	46	29·8	94	980·7609	0·0052	0·0020
792	Smith Corner...............	1945	65	10·0	46	30·3	109	·7519	− ·0030	− ·0068
793	McNamee...................	1944	66	16·7	46	30·6	140	·7509	− ·0016	− ·0064
794	(Mortimer).................	1944	65	16·9	46	30·7	205	·7464	− ·0001	− ·0071
795	Bath........................	1947	67	35·0	46	30·8	218	·7277	− ·0178	− ·0252
796	Argyle......................	1950	67	20·8	46	30·9	1,056	·6609	− ·0059	− ·0418
797	St. Pierre..................	1944	64	45·3	46	31·2	99	·7593	·0021	− ·0013
798	Carroll.....................	1944	66	13·9	46	31·4	165	·7546	·0032	− ·0024
799	(Mortimer).................	1944	65	18·0	46	32·0	228	·7466	·0002	− ·0075
800	Juniper.....................	1950	67	10·2	46	32·8	835	·6765	− ·0140	− ·0424

PRINCIPAL FACTS FOR GRAVITY STATIONS—NEW BRUNSWICK—*Continued*

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name								Free Air	Bouguer
			°	′	°	′	Ft.			
801	Ste. Anne de Kent..........	1944	64	46·3	46	32·8	82	980·7576	−0·0037	−0·0065
802	(Bass River)...............	1945	65	06·5	46	33·2	87	·7599	− ·0015	− ·0045
803	(Kent Junction)............	1944	65	19·4	46	33·4	227	·7492	·0007	− ·0071
804	Doaktown...................	1944	66	07·4	46	33·5	124	·7447	− ·0136	− ·0179
805	Upper Kent.................	1944	67	42·1	46	34·3	276	·7275	− ·0177	− ·0271
806	(Ste. Anne)................	1944	64	47·6	46	34·7	36	·7575	− ·0109	− ·0121
807	Blissfield.................	1944	66	04·2	46	34·8	251	·7457	− ·0027	− ·0112
808	Kent Junction..............	1944	65	20·3	46	34·9	265	·7495	·0023	− ·0067
809	(E. Galloway)..............	1944	64	48·9	46	36·6	108	·7499	− ·0146	− ·0183
810	(Kent Junction)............	1944	65	21·3	46	36·7	260	·7521	·0018	− ·0071
811	Aldonane...................	1945	65	03·3	46	37·0	127	980·7630	−0·0004	−0·0047
812	Weaver.....................	1944	65	58·0	46	37·0	344	·7557	·0128	·0010
813	(Rexton)...................	1944	64	51·0	46	38·3	26	·7613	− ·0135	− ·0143
814	(Belliveau)................	1944	65	21·9	46	38·3	275	·7523	·0010	− ·0084
815	Kilburn....................	1947	67	41·8	46	38·3	286	·7353	− ·0150	− ·0248
816	Upper Blackville...........	1944	65	51·9	46	38·9	232	·7846	·0283	·0204
817	Rexton.....................	1944	64	52·9	46	39·3	25	·7650	− ·0114	− ·0123
818	Belliveau..................	1944	65	22·7	46	40·0	273	·7538	− ·0003	− ·0096
819	Richibucto.................	1944	64	52·3	46	40·3	17	·7681	− ·0105	− ·0111
820	Acadieville................	1944	65	23·7	46	41·5	310	·7550	·0021	− ·0085
821	(Richibucto)...............	1944	64	52·5	46	41·9	11	980·7720	−0·0096	−0·0099
822	(Richibucto)...............	1944	64	54·9	46	42·5	25	·7764	− ·0048	− ·0057
823	(Rogersville)..............	1944	65	24·8	46	42·8	280	·7597	·0020	− ·0075
824	(St. Louis de Kent)........	1944	64	57·0	46	43·3	42	·7816	·0008	− ·0007
825	Blackville.................	1944	65	49·5	46	43·7	90	·7895	·0127	·0096
826	Rogersville................	1944	65	25·7	46	43·9	315	·7600	·0039	− ·0068
827	Perth......................	1944	67	42·1	46	44·1	263	·7481	− ·0131	− ·0220
828	Perth......................	1950	67	42·0	46	44·2	262	·7481	− ·0134	− ·0223
829	(St. Louis de Kent)........	1944	64	59·3	46	44·8	74	·7852	·0052	·0026
830	(North Rogersville)........	1944	65	26·8	46	45·2	270	·7644	·0022	− ·0070
831	(Kouchibouguac)............	1944	65	01·0	46	46·0	134	980·7829	0·0067	0·0021
832	(Renous River).............	1945	66	16·7	46	46·7	598	·7467	·0131	− ·0072
833	Collette...................	1944	65	27·7	46	46·8	170	·7731	− ·0009	− ·0067
834	Red Rapids.................	1945	67	30·2	46	46·8	353	·7543	− ·0025	− ·0145
835	Kouchibouguac..............	1944	65	03·2	46	47·3	75	·7882	·0045	·0019
836	(Renous River).............	1945	66	27·8	46	47·4	938	·7106	·0079	− ·0240
837	(Renous River).............	1945	66	11·8	46	47·6	288	·7690	·0049	− ·0049
838	(Collette).................	1944	65	27·2	46	48·2	125	·7796	− ·0007	− ·0050
839	Aroostook..................	1947	67	43·1	46	48·2	276	·7535	− ·0126	− ·0220
840	(Kouchibouguac)............	1944	65	04·3	46	48·6	85	·7882	·0034	·0005
841	Renous.....................	1944	65	47·6	46	48·9	71	980·7924	0·0059	0·0035
842	(Renous River).............	1945	66	06·3	46	49·4	177	·7801	·0028	− ·0032
843	Rosaireville...............	1945	65	17·9	46	49·5	282	·7686	·0010	− ·0086
844	(Renous River).............	1945	66	05·9	46	49·7	170	·7814	·0030	− ·0028
845	(Renous River).............	1945	65	55·9	46	49·8	82	·7912	·0044	·0016
846	(Laketon)..................	1944	65	05·9	46	50·0	130	·7853	·0028	− ·0016
847	(Wiseman Brook)............	1944	65	26·9	46	50·0	120	·7860	·0026	− ·0015
848	(Three Brooks).............	1950	67	26·1	46	50·5	394	·7642	·0057	− ·0077
849	Park.......................	1944	65	43·6	46	51·0	87	·7932	·0050	·0020
850	Laketon....................	1944	65	07·6	46	51·2	190	·7795	·0007	− ·0058

PRINCIPAL FACTS FOR GRAVITY STATIONS—NEW BRUNSWICK—*Continued*

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name								Free Air	Bouguer
			°	′	°	′	Ft.			
851	Wiseman Brook	1944	65	26·4	46	51·7	80	980·7941	0·0042	0·0015
852	(Wiseman Brook)	1944	65	28·4	46	52·3	80	·7949	·0041	·0014
853	(Laketon)	1944	65	09·2	46	52·6	183	·7799	− ·0016	− ·0078
854	(Upper Baie du Vin)	1944	65	10·2	46	53·3	116	·7857	− ·0032	− ·0071
855	Barnaby River	1944	65	30·8	46	53·3	80	·7953	·0030	·0003
856	Parker	1944	65	39·2	46	53·3	55	·7960	·0014	− ·0005
857	Plaster Rock	1950	67	24·4	46	53·4	467	·7655	·0095	− ·0063
858	(Plaster Rock)	1945	67	04·1	46	53·6	1,265	·7172	·0360	− ·0071
859	(Plaster Rock)	1945	67	14·5	46	53·7	600	·7655	·0215	·0011
860	Plaster Rock	1945	67	23·0	46	54·3	384	·7732	·0080	− ·0051
861	Upper Baie du Vin	1944	65	11·9	46	54·4	179	980·7862	0·0016	−0·0045
862	(Upper Baie du Vin)	1944	65	13·3	46	55·0	160	·7910	·0037	− ·0017
863	(Reynolds)	1944	65	31·1	46	55·1	165	·7987	·0077	·0061
864	Cliffordvale	1944	67	42·8	46	55·3	595	·7414	− ·0054	− ·0257
865	Redmondville	1944	65	14·6	46	55·6	141	·7971	·0072	·0024
866	Limestone	1947	67	42·4	46	55·6	335	·7579	− ·0138	− ·0252
867	Lower Derby	1944	65	37·2	46	55·9	68	·8054	·0081	·0058
868	(Redmondville)	1944	65	16·9	46	56·8	105	·8066	·0115	·0079
869	Reynolds	1944	65	32·0	46	56·8	120	·8075	·0138	·0097
870	Blue Bell	1950	67	32·1	46	57·0	741	·7471	·0115	− ·0137
871	Sunny Corner	1945	65	49·5	46	57·6	65	980·8114	0·0108	0·0091
872	(Black River)	1944	65	19·3	46	57·9	84	·8130	·0142	·0113
873	South Nelson Road	1944	65	33·4	46	57·9	51	·8162	·0143	·0126
874	(Black River)	1945	65	19·5	46	58·0	77	·8138	·0142	·0116
875	Whitney	1944	65	43·6	46	58·0	50	·8129	·0108	·0091
876	(Black River)	1944	65	21·1	46	58·5	119	·8123	·0159	·0118
877	(Black River)	1944	65	23·1	46	59·1	115	·8158	·0181	·0142
878	New Denmark	1950	67	35·3	46	59·8	662	·7551	·0079	− ·0148
879	(New Castle Bridge)	1944	65	32·8	47	00·0	45	·8128	·0072	·0057
880	(Chatham)	1944	65	25·3	47	00·4	55	·8234	·0181	·0162
881	Oxbow	1950	67	17·7	47	00·6	588	980·7646	0·0092	−0·0109
882	(Chatham)	1944	65	26·3	47	01·1	100	·8183	·0162	·0128
883	Grand Falls	1950	67	44·3	47	02·7	511	·7583	− ·0075	− ·0249
884	Grand Falls	1944	67	44·8	47	02·9	502	·7585	− ·0085	− ·0256
885	(Ferry Road Corner)	1944	65	28·1	47	03·0	55	·8173	·0082	·0063
886	(Ferry Road Corner)	1944	65	29·3	47	03·6	260	·8044	·0137	·0048
887	(Ferry Road Corner)	1944	65	26·3	47	03·8	92	·8175	·0107	·0075
888	(Ashton Hill)	1945	65	40·5	47	03·9	300	·8009	·0134	·0032
889	(Bartibog Bridge)	1944	65	23·9	47	04·6	50	·8217	·0097	·0080
890	(Little Bartibog)	1944	65	28·2	47	05·4	305	·8044	·0152	·0048
891	(Bartibog Bridge)	1944	65	21·6	47	05·5	60	980·8228	0·0103	0·0083
892	(Bartibog Bridge)	1944	65	19·7	47	06·2	50	·8250	·0106	·0089
893	Bellefleur	1947	67	52·4	47	06·7	480	·7646	− ·0101	− ·0265
894	(Little Bartibog)	1944	65	27·2	47	06·8	120	·8193	·0106	·0065
895	The Willows	1944	65	17·3	47	07·0	37	·8278	·0110	·0097
896	(Ashton Hill)	1945	65	50·0	47	07·2	125	·8146	·0058	·0015
897	Beaver Brook	1945	65	36·3	47	07·6	330	·8034	·0132	·0020
898	(Oxbow)	1950	67	15·6	47	07·6	689	·7665	·0101	− ·0134
899	(The Willows)	1944	65	15·6	47	07·9	40	·8299	·0120	·0106
900	(Little Bartibog)	1944	65	26·0	47	08·4	260	·8124	·0145	·0056

PRINCIPAL FACTS FOR GRAVITY STATIONS—NEW BRUNSWICK—*Continued*

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name								Free Air	Bouguer
			°	′	°	′	Ft.			
901	Barryville	1944	65	14·2	47	09·6	40	980·8311	0·0107	0·0093
902	(Bartibog)	1944	65	25·1	47	09·6	225	·8151	·0121	·0044
903	St. Leonard	1944	67	55·7	47	10·0	467	·7710	— ·0099	— ·0258
904	Bartibog	1944	65	24·4	47	11·2	123	·8225	·0075	·0033
905	(New Jersey)	1944	65	13·0	47	11·4	63	·8314	·0104	·0083
906	Mill Stream	1945	67	48·7	47	11·7	851	·7511	·0037	— ·0252
907	New Jersey	1944	65	11·3	47	12·4	73	·8341	·0126	·0101
908	Bartibog	1944	65	24·3	47	12·4	285	·8123	·0107	·0010
909	(New Jersey)	1944	65	09·7	47	13·4	78	·8372	·0146	·0120
910	(Bartibog)	1944	65	24·3	47	14·0	230	·8171	·0079	·0001
911	(Rivière des Caches)	1944	65	07·1	47	14·1	27	980·8428	0·0143	0·0134
912	Nictau	1950	67	09·3	47	14·2	554	·7803	·0013	— ·0176
913	Quisibis	1947	68	03·0	47	15·1	756	·7783	·0169	— ·0088
914	Neguac	1944	65	04·0	47	15·6	18	·8442	·0127	·0121
915	(Eskedelloc Brook)	1944	65	24·3	47	15·6	310	·8160	·0120	·0014
916	(Neguac)	1944	65	02·9	47	16·5	27	·8465	·0144	·0135
917	Eskedelloc Brook	1944	65	24·5	47	17·2	285	·8167	·0079	— ·0018
918	(Grand River)	1945	67	41·0	47	17·4	772	·7651	·0018	— ·0245
919	Canon Brook	1947	68	34·6	47	17·4	606	·7648	— ·0141	— ·0348
920	Albertine	1947	68	27·3	47	17·5	492	·7754	— ·0144	— ·0312
921	(Covedell)	1944	65	01·0	47	17·7	50	980·8464	0·0147	0·0130
922	Baker Brook	1947	68	31·4	47	17·9	512	·7729	— ·0156	— ·0331
923	(Tabusintac River)	1944	65	25·3	47	18·8	341	·8106	·0047	— ·0069
924	Covedell P.O.	1944	65	00·4	47	19·2	23	·8514	·0150	·0142
925	Green River	1944	68	09·6	47	19·3	477	·7794	— ·0145	— ·0308
926	(Tabusintac River)	1944	65	25·8	47	20·4	268	·8130	— ·0022	— ·0113
927	Lac Baker	1947	68	39·4	47	20·4	682	·7604	— ·0159	— ·0391
928	(Tabusintac)	1944	65	00·0	47	20·9	20	·8547	·0154	·0147
929	St. Basil	1947	68	14·4	47	21·4	474	·7818	— ·0156	— ·0317
930	Edmunston	1944	68	19·6	47	21·7	489	·7820	— ·0144	— ·0311
931	Grand River	1945	67	37·2	47	22·1	727	980·7741	—0·0005	—0·0253
932	(Brantville)	1944	64	58·1	47	22·2	48	·8506	·0120	·0104
933	(Pisiquit Brook)	1944	65	26·5	47	22·2	450	·7955	— ·0053	— ·0206
934	Boundary Station	1947	68	43·6	47	22·3	684	·7607	— ·0183	— ·0416
935	Bear House	1950	66	19·6	47	23·0	750	·7727	— ·0010	— ·0266
936	(Brantville)	1944	64	56·8	47	23·5	35	·8492	·0074	·0062
937	Bear House	1950	66	11·2	47	23·5	599	·7928	·0040	— ·0164
938	Pisiquit Brook	1944	65	27·1	47	23·7	500	·7917	— ·0067	— ·0237
939	Popple	1950	66	30·7	47	24·1	802	·7878	·0173	— ·0100
940	(Legère)	1944	64	56·4	47	24·8	45	·8501	·0073	·0058
941	(Jardine Brook)	1945	67	28·4	47	25·0	930	980·7707	0·0109	—0·0208
942	Middle Brook	1944	65	28·0	47	25·4	510	·7898	— ·0101	— ·0275
943	(Bear House)	1950	66	11·9	47	26·2	1,094	·7667	·0205	— ·0167
944	(County Boundary)	1944	64	55·4	47	26·3	28	·8535	·0068	·0059
945	(Popple)	1950	66	44·7	47	26·9	1,118	·7577	·0127	— ·0254
946	Foy Brook	1944	65	28·9	47	27·0	507	·7988	— ·0038	— ·0211
947	(Popple)	1950	66	37·7	47	27·0	1,315	·7511	·0245	— ·0203
948	(Sheila Bridge)	1944	64	54·6	47	27·9	12	·8569	·0063	·0059
949	(Rio Grande)	1950	66	04·2	47	28·2	1,016	·8009	·0444	·0098
950	(Foy Brook)	1944	65	29·5	47	28·5	520	·8052	·0015	— ·0162

PRINCIPAL FACTS FOR GRAVITY STATIONS—NEW BRUNSWICK—*Concluded*

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name								Free Air	Bouguer
			°	′	°	′	Ft.			
951	(Sheila)	1944	64	55·2	47	29·2	14	980·8607	0·0083	0·0078
952	Interprovincial Boundary	1944	68	28·6	47	29·3	510	·7863	– ·0195	– ·0369
953	(Foy Brook)	1944	65	29·8	47	29·4	480	·8102	·0014	– ·0149
954	St. Quenten	1945	67	23·4	47	30·2	915	·7780	·0090	– ·0222
955	Tracadie	1944	64	54·8	47	30·8	38	·8642	·0118	·0105
956	(Bass River)	1944	65	30·5	47	30·9	400	·8186	·0000	– ·0136
957	(Rio Grande)	1950	65	57·5	47	31·4	781	·8086	– ·0265	– ·0015
958	(Tracadie)	1944	64	55·0	47	32·2	13	·8734	·0165	·0161
959	(Bass River)	1944	65	32·0	47	32·3	235	·8279	– ·0083	– ·0163
960	Bass River	1944	65	33·1	47	33·0	125	·8312	– ·0163	– ·0206
961	(Rio Grande)	1950	65	50·1	47	33·5	418	980·8204	–0·0003	–0·0146
962	Lozier Settlement	1944	64	56·0	47	33·8	40	·8748	·0180	·0166
963	(East Bathurst)	1944	65	34·5	47	34·2	140	·8262	– ·0217	– ·0265
964	Rio Grande	1950	65	45·8	47	35·0	239	·8214	– ·0185	– ·0266
965	(East Bathurst)	1944	65	36·0	47	35·2	172	·8262	– ·0203	– ·0262
966	(Lozier Settlement)	1944	64	55·0	47	35·3	70	·8747	·0186	·0162
967	(Six Roads)	1944	64	53·2	47	36·3	63	·8774	·0190	·0169
968	East Bathurst	1944	65	37·2	47	36·3	71	·8343	– ·0233	– ·0257
969	Bathurst	1950	65	40·3	47	37·1	48	·8376	– ·0233	– ·0250
970	Bathurst	1944	65	39·0	47	37·2	20	·8395	– ·0242	– ·0249
971	(Six Roads)	1944	64	52·2	47	38·0	8	980·8831	0·0171	0·0168
972	Kedgwick	1945	67	20·6	47	38·5	897	·7912	·0080	– ·0226
973	(Pokemouche)	1944	64	52·6	47	39·8	18	·8824	·0146	·0140
974	Salmon Beach	1944	65	32·1	47	39·8	30	·8620	– ·0047	– ·0057
975	Upper Pokemouche	1944	64	52·7	47	41·2	50	·8796	·0127	·0110
976	Janeville	1944	65	26·4	47	41·3	65	·8745	·0088	·0066
977	(Blanchard Settlement)	1944	64	53·5	47	42·6	50	·8805	·0115	·0098
978	Clifton	1944	65	22·5	47	43·7	119	·8706	·0064	·0023
979	(Blanchard Settlement)	1944	64	54·6	47	44·3	35	·8831	·0101	·0089
980	Nigado	1944	65	43·1	47	44·3	51	·8744	·0029	·0012
981	Bertrand	1944	65	04·0	47	45·4	70	980·8799	0·0086	0·0062
982	(Caraquet)	1944	64	55·3	47	45·7	50	·8820	·0084	·0067
983	Oliver Siding	1945	67	12·9	47	45·9	1,010	·7949	·0112	– ·0232
984	New Bandon	1944	65	17·5	47	46·0	146	·8714	·0063	·0014
985	Caraquet	1944	64	58·0	47	47·4	88	·8774	·0049	·0019
986	Grande Anse	1944	65	12·6	47	48·1	80	·8756	·0011	– ·0016
987	(Millerville)	1945	67	04·3	47	49·2	795	·8096	·0008	– ·0263
988	(Dugas)	1944	65	07·8	47	49·4	30	·8795	– ·0017	– ·0027
989	Robinsonville	1945	66	56·6	47	52·7	100	·8545	– ·0250	– ·0284
990	Belledune	1944	65	48·8	47	53·1	40	·8753	– ·0104	– ·0118
991	Nash Creek	1944	66	04·6	47	55·4	21	980·8779	–0·0130	–0·0137
992	Tidehead	1945	66	46·5	47	58·8	33	·8635	– ·0314	– ·0325
993	Charlo Station	1944	66	18·4	47	59·6	53	·8882	– ·0060	– ·0078
994	Campbellton	1944	66	40·8	48	00·3	42	·8694	– ·0268	– ·0283
995	Dalhousie Junction	1944	66	30·5	48	02·5	78	·8759	– ·0203	– ·0229

PRINCIPAL FACTS FOR GRAVITY STATIONS—NOVA SCOTIA

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name								Free Air	Bouguer
			°	′	°	′	Ft.			
1	Barrington Passage	1945	65	36·5	43	31·6	10	980·4918	−0·0038	−0·0041
2	Clyde River	1945	65	28·6	43	38·0	25	·4991	− ·0046	− ·0055
3	D'Entremont	1945	65	45·9	43	38·7	21	·5080	·0029	·0022
4	Sandy Point	1950	65	18·0	43	41·0	36	·5091	·0019	− ·0007
5	Lydgate	1950	65	07·4	43	43·0	58	·5091	·0010	− ·0011
6	(Birchtown)	1945	65	23·0	43	44·3	122	·5042	·0001	− ·0041
7	Upper Wedgeport	1950	65	59·3	43	45·3	30	·5047	− ·0096	− ·0106
8	(Shelburne)	1945	65	19·0	43	45·9	71	·5103	− ·0010	− ·0034
9	Central Argyle	1945	65	50·2	43	46·2	43	·5179	− ·0035	·0021
10	Jordan Falls	1945	65	13·9	43	48·9	27	·5167	− ·0032	− ·0042
11	(Plymouth)	1950	66	01·7	43	49·0	46	980·5172	−0·0011	−0·0026
12	Lower Ohio	1950	65	22·0	43	50·2	134	·5115	− ·0003	− ·0049
13	Yarmouth	1950	66	07·3	43	50·2	40	·5469	·0262	·0248
14	Sable River	1945	65	03·9	43	50·5	19	·5111	− ·0120	− ·0127
15	Yarmouth	1945	66	07·1	43	50·7	31	·5493	·0270	·0260
16	Tusket	1945	65	58·3	43	51·7	35	·5210	− ·0024	− ·0036
17	Middle Ohio	1950	65	24·0	43	54·7	205	·5183	·0064	− ·0006
18	(South Canaan)	1950	65	54·1	43	56·2	86	·5234	− ·0020	− ·0049
19	Port Mouton	1945	64	50·6	43	56·3	60	·5104	− ·0176	− ·0196
20	White Point Beach	1950	64	45·5	43	57·4	73	·5108	− ·0176	− ·0201
21	Upper Ohio	1950	65	25·9	43	58·8	214	980·5211	0·0039	−0·0034
22	Port Maitland	1945	66	08·8	43	58·9	84	·5551	·0255	·0226
23	(Carleton)	1950	65	53·2	44	00·0	104	·5208	− ·0086	− ·0121
24	Liverpool	1950	64	42·5	44	02·7	16	·5259	− ·0158	− ·0164
25	(Carleton)	1950	65	54·7	44	04·5	120	·5360	·0014	− ·0027
26	(Milton)	1950	64	46·5	44	04·8	96	·5222	− ·0152	− ·0184
27	Mavillette	1950	66	11·2	44	06·1	14	·5712	·0241	·0237
28	(Milton)	1950	64	56·2	44	08·3	155	·5207	− ·0164	− ·0217
29	Milk Village	1945	64	38·9	44	08·7	30	·5311	− ·0183	− ·0193
30	(Carleton)	1950	65	56·1	44	09·0	223	·5453	·0136	·0060
31	(Milton)	1950	64	59·8	44	09·4	266	980·5209	−0·0073	−0·0164
32	Meteghan	1945	66	09·7	44	11·3	58	·5754	·0248	·0228
33	(Middlefield)	1950	64	50·9	44	12·0	273	·5181	− ·0134	− ·0228
34	Pleasantfield	1950	64	54·3	44	14·4	319	·5228	− ·0080	− ·0189
35	Italy Cross	1950	64	32·8	44	15·8	199	·5359	− ·0083	− ·0151
36	Saulnierville	1950	66	07·9	44	15·9	61	·5768	·0195	·0174
37	(New Tusket)	1950	65	54·5	44	16·1	332	·5503	·0182	·0069
38	(Greenfield)	1950	64	49·3	44	17·7	260	·5330	− ·0083	− ·0172
39	(South Brookfield)	1950	64	57·4	44	19·4	253	·5235	− ·0211	− ·0297
40	Church Point	1945	66	06·9	44	20·3	53	·5851	·0204	·0186
41	Upper Chelsea	1950	64	46·0	44	20·8	349	980·5351	−0·0026	−0·0144
42	Caledonia	1950	65	02·0	44	22·5	302	·5260	− ·0186	− ·0289
43	Bridgewater	1945	64	30·9	44	22·7	11	·5575	− ·0148	− ·0151
44	Lunenburg	1950	64	19·3	44	22·8	33	·5586	− ·0118	− ·0129
45	(Weymouth)	1950	65	56·3	44	22·9	259	·5584	·0092	·0004
46	East Ferry	1950	66	12·1	44	23·5	147	·5788	·0181	·0131
47	Baker Settlement	1950	64	40·7	44	23·8	293	·5459	− ·0015	− ·0115
48	Weymouth	1945	65	59·8	44	24·7	54	·5841	·0129	·0110
49	(North Brookfield)	1950	64	59·5	44	25·5	325	·5290	− ·0179	− ·0290
50	(Kempt)	1945	65	08·3	44	25·9	399	·5363	− ·0043	− ·0179

PRINCIPAL FACTS FOR GRAVITY STATIONS—NOVA SCOTIA—*Continued*

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name		°	′	°	′	Ft.		Free Air	Bouguer
51	Mahone Bay	1945	64	22·8	44	27·2	85	980·5590	−0·0131	−0·0160
52	Colpton	1945	64	50·9	44	27·3	345	·5408	− ·0069	− ·0187
53	(Doucetteville)	1950	65	47·8	44	27·7	434	·5567	·0167	− ·0180
54	Northfield	1945	64	36·7	44	28·0	130	·5540	− ·0151	− ·0195
55	(Morganville)	1950	65	33·7	44	28·6	586	·5318	·0047	− ·0152
56	Sandy Cove	1950	66	05·4	44	29·5	17	·5869	·0050	·0044
57	Plympton	1945	65	54·8	44	30·1	80	·5888	·0119	·0092
58	(Mahone Bay)	1950	64	26·8	44	30·6	270	·5440	− ·0158	− ·0250
59	North Range	1950	65	50·6	44	30·7	305	·5744	·0178	·0074
60	Lake Munro	1945	65	20·6	44	31·6	524	·5344	− ·0030	− ·0209
61	Morganville	1950	65	37·1	44	31·8	480	980·5493	0·0074	−0·0089
62	Chester	1950	64	14·5	44	32·4	48	·5562	− ·0272	− ·0288
63	E. Chester	1945	64	14·2	44	32·7	46	·5571	− ·0269	− ·0284
64	New Germany	1945	64	43·2	44	32·9	258	·5548	− ·0095	− ·0183
65	(Bear River)	1950	65	39·9	44	33·4	464	·5660	·0202	·0045
66	Chester Basin	1950	64	18·5	44	34·0	76	·5476	− ·0356	− ·0382
67	Rossway	1950	65	55·0	44	34·7	156	·5893	·0127	·0073
68	(Milford)	1945	65	24·8	44	34·8	514	·5450	·0018	− ·0157
69	Acaciaville	1945	65	46·6	44	34·8	174	·5960	·0209	·0150
70	(Mahone Bay)	1950	64	32·3	44	36·1	576	·5191	− ·0201	− ·0398
71	Smith's Cove	1950	65	43·8	44	36·5	83	980·6050	0·0188	0·0159
72	Clementsvale	1950	65	34·1	44	36·9	350	·5802	·0184	·0065
73	Cherryfield	1945	64	48·5	44	37·1	344	·5335	− ·0290	− ·0408
74	Digby	1950	65	45·4	44	37·4	35	·6070	·0149	·0137
75	Maplewood	1950	64	37·5	44	37·7	406	·5412	− ·0164	− ·0303
76	(Chester Basin)	1950	64	21·5	44	38·0	249	·5255	− ·0474	− ·0559
77	Hubbard's	1950	64	03·7	44	38·4	68	·5492	·0413	− ·0436
78	Deep Brook	1950	65	39·1	44	38·4	46	·6127	·0201	·0186
79	Halifax	1950	63	34·4	44	38·9	21	·5787	− ·0170	− ·0177
80	(Annapolis Royal)	1945	65	28·0	44	39·5	423	·5708	·0120	− ·0024
81	Dartmouth	1944	63	34·3	44	39·9	13	980·5831	−0·0149	−0·0153
82	Timberlea	1950	63	44·6	44	39·9	265	·5493	− ·0250	− ·0340
83	Clementsport	1945	65	36·7	44	39·9	72	·6121	·0197	·0172
84	(Chester Basin)	1950	64	17·2	44	40·3	492	·5130	− ·0404	− ·0572
85	Port Wade	1950	65	42·8	44	40·6	41	·6106	·0143	·0128
86	(New Ross)	1950	64	25·2	44	41·4	527	·5110	− ·0409	− ·0588
87	Prim Point	1950	65	47·2	44	41·4	72	·6112	·0166	·0141
88	French Village	1950	63	53·2	44	41·7	79	·5587	·0357	− ·0384
89	Upper Clements	1950	65	35·2	44	41·8	73	·6098	·0147	·0122
90	(Dalhousie)	1945	64	55·7	44	42·1	640	·5329	− ·0094	− ·0312
91	(Chester Basin)	1945	64	15·6	44	42·9	461	980·5218	−0·0385	−0·0542
92	Lower Granville	1950	65	36·2	44	43·0	57	·6126	·0141	·0122
93	Dalhousie West	1950	65	14·2	44	43·2	785	·5397	·0093	− ·0174
94	(Maplewood)	1950	64	41·6	44	43·3	666	·5154	− ·0263	− ·0490
95	Bedford	1950	63	40·1	44	43·7	43	·5818	− ·0191	− ·0205
96	Porter Lake	1944	63	18·5	44	44·3	13	·5804	− ·0242	− ·0246
97	Annapolis Royal	1950	65	31·1	44	44·8	20	·6105	·0059	·0052
98	(New Ross)	1950	64	28·5	44	46·0	511	·5213	− ·0389	− ·0564
99	(Bridgetown)	1950	65	14·6	44	46·2	705	·5569	·0146	− ·0094
100	(Delap Cove)	1950	65	37·3	44	46·3	152	·6170	·0225	·0174

PRINCIPAL FACTS FOR GRAVITY STATIONS—NOVA SCOTIA—*Continued*

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name								Free Air	Bouguer
			°	′	°	′	Ft.			
101	Jeddore Oyster Pond........	1950	63	00·5	44	46·8	5	980·5830	—0·0260	—0·0262
102	Waverley..................	1944	63	36·2	44	46·8	74	·5837	— ·0188	— ·0214
103	Chester Basin..............	1950	64	14·4	44	46·8	507	·5252	·0366	— ·0539
104	Smith Settlement............	1950	63	06·2	44	47·1	36	·5812	— ·0254	— ·0266
105	Musquodoboit Harbour......	1950	63	09·0	44	47·2	56	·5804	— ·0244	— ·0263
106	Maroon Hill................	1950	63	43·5	44	47·5	418	·5732	·0019	— ·0123
107	Tupperville................	1950	65	22·0	44	48·1	19	·6075	·0022	— ·0028
108	Tangier....................	1944	62	42·5	44	48·3	13	·5996	— ·0110	— ·0114
109	(New Albany)..............	1945	65	03·3	44	48·3	571	·5696	·0115	— ·0079
110	Parker's Cove..............	1950	65	31·9	44	48·8	156	·6106	·0127	·0074
111	Ship Harbour..............	1944	62	53·1	44	49·1	23	980·5860	—0·0248	—0·0256
112	(Lake Paul)................	1950	64	40·8	44	49·2	628	·5274	— ·0266	— ·0480
113	Spry Harbour..............	1950	62	38·2	44	49·3	6	·6027	— ·0100	— ·0103
114	(Musquodoboit Harbour)....	1950	63	12·1	44	49·8	83	·5712	— ·0350	— ·0379
115	Bridgetown................	1945	65	17·7	44	50·3	22	·6057	— ·0070	— ·0078
116	(Smith Corner)............	1945	64	13·2	44	50·9	343	·5561	— ·0273	— ·0390
117	(New Ross Road)..........	1950	64	31·3	44	51·8	693	·5256	— ·0263	— ·0499
118	(Sheet Harbour)............	1950	62	34·5	44	52·2	90	·6007	— ·0084	— ·0115
119	(Bridgetown)...............	1950	65	19·0	44	52·4	770	·5669	·0213	— ·0049
120	Lawrencetown.............	1950	65	09·7	44	53·0	77	·6189	·0073	·0047
121	Phinney Cove..............	1950	65	23·8	44	53·1	80	980·6161	0·0046	0·0019
122	Mount Uniacke............	1950	63	50·0	44	53·4	522	·5697	— ·0006	— ·0184
123	Grand Lake................	1944	63	35·7	44	53·5	60	·5983	— ·0157	— ·0177
124	Hampton..................	1950	65	20·3	44	54·4	169	·6102	·0051	— ·0006
125	Lake George..............	1950	64	41·7	44	55·0	855	·5342	— ·0073	— ·0364
126	Sheet Harbour............	1944	62	32·7	44	55·4	8	·6215	— ·0002	— ·0005
127	(New Ross Road)..........	1950	64	31·2	44	55·9	613	·5481	— ·0174	— ·0383
128	Meagher Grant............	1950	63	14·7	44	56·0	69	·6026	— ·0143	— ·0166
129	Middleton.................	1945	65	04·7	44	56·6	70	·6303	·0126	·0102
130	(Sheet Harbour)............	1950	62	36·7	44	57·2	94	·6129	— ·0035	— ·0067
131	(Newport Corner)..........	1950	63	56·1	44	57·5	585	980·5830	0·0124	—0·0075
132	Newport...................	1950	64	04·0	44	57·5	112	·6068	— ·0083	— ·0121
133	Elmsdale..................	1944	63	30·3	41	58·0	51	·6130	— ·0086	— ·0103
134	Mount Hanly..............	1950	65	10·6	44	58·1	453	·6024	·0184	·0030
135	(Elderbank)...............	1950	63	14·0	44	58·3	78	·6149	— ·0046	— ·0072
136	Moose River..............	1944	62	15·2	44	58·4	13	·6288	·0030	·0026
137	(Morristown)..............	1950	64	45·2	44	59·0	400	·6057	·0155	·0019
138	Windsor...................	1950	64	08·3	44	59·8	25	·6159	— ·0102	— ·0117
139	Windsor...................	1950	64	08·2	44	59·9	28	·6158	— ·0108	— ·0118
140	(Kingston).................	1950	65	00·0	45	00·4	352	·6114	·0145	·0025
141	(Sheet Harbour)............	1950	62	43·5	45	00·6	303	980·6011	—0·0007	—0·0110
142	(South Alton)..............	1950	64	32·2	45	00·7	725	·5821	·0199	— ·0048
143	Auburn....................	1945	64	52·1	45	01·2	95	·6329	·0106	·0074
144	Liscomb...................	1944	61	59·5	45	01·9	13	·6312	·0001	— ·0003
145	Gays River................	1950	63	21·3	45	02·0	84	·6218	— ·0027	— ·0056
146	Woodville..................	1950	63	56·2	45	02·0	187	·6090	— ·0058	— ·0121
147	(Middle Musquodoboit)......	1950	63	15·7	45	02·1	165	·6162	— ·0008	— ·0064
148	(Milford Station)...........	1950	63	26·2	45	02·4	55	·6218	— ·0061	— ·0079
149	Nine Mile River...........	1950	63	34·3	45	02·5	88	·6194	— ·0055	— ·0085
150	Berwick...................	1950	64	44·3	45	02·5	138	·6300	·0099	·0051

PRINCIPAL FACTS FOR GRAVITY STATIONS—NOVA SCOTIA—*Continued*

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name								Free Air	Bouguer
			°	′	°	′	Ft.			
151	Middle Musquodoboit.......	1950	63	09·5	45	02·6	116	980·6181	−0·0043	−0·0083
152	Margaretville..............	1950	65	03·7	45	02·9	56	·6306	·0021	·0002
153	Waterville..................	1945	64	40·7	45	03·2	91	·6322	·0066	·0035
154	Rawdon Mine..............	1950	63	45·9	45	03·3	492	·6032	·0151	− ·0017
155	Coldbrook..................	1950	64	35·0	45	04·0	68	·6394	·0104	·0081
156	Mosherville.................	1945	63	57·4	45	04·4	36	·6212	− ·0114	− ·0126
157	Upper Musquodoboit........	1950	62	51·4	45	04·5	522	·6002	·0131	− ·0047
158	Somerset....................	1950	64	45·0	45	04·6	139	·6337	·0105	·0057
159	Kentville....................	1945	64	29·8	45	04·7	35	·6446	·0114	·0102
160	Lower Burlington...........	1950	64	07·2	45	05·0	26	·6313	− ·0033	− ·0041
161	Reid..........................	1950	63	04·0	45	05·2	141	980·6225	−0·0014	−0·0062
162	Shubenacadie..............	1950	63	24·4	45	05·2	58	·6235	− ·0083	− ·0103
163	Wolfville....................	1950	64	22·0	45	05·2	46	·6451	·0122	·0107
164	Wolfville....................	1950	64	21·8	45	05·5	28	·6460	·0109	·0100
165	Roulston Corner............	1950	63	38·7	45	05·6	369	·6110	·0079	− ·0047
166	Garland.....................	1950	64	45·9	45	06·0	682	·5981	·0237	·0006
167	Kent.........................	1950	63	01·6	45	06·1	168	·6233	·0005	− ·0052
168	Clarksville..................	1950	63	49·9	45	06·1	71	·6136	− ·0183	− ·0208
169	Grand Pré...................	1945	64	18·6	45	06·5	28	·6454	·0088	·0079
170	Centreville..................	1950	64	31·7	45	07·8	90	·6442	·0115	·0084
171	Harbourville................	1950	64	47·1	45	07·9	449	980·6100	0·0109	−0·0044
172	Stewiacke...................	1944	63	20·9	45	08·3	82	·6301	− ·0041	− ·0069
173	Upper Musquodoboit........	1950	62	56·9	45	08·4	173	·6289	·0031	− ·0028
174	Hillaton.....................	1950	64	26·7	45	08·8	32	·6474	·0078	− ·0034
175	Sherbrooke.................	1944	61	58·5	45	09·0	33	·6393	− ·0005	− ·0016
176	(Vernon Mines)............	1950	64	35·8	45	09·0	613	·6075	·0223	·0013
177	Harbourville................	1950	64	48·7	45	09·1	34	·6337	− ·0062	− ·0073
178	Kingsport...................	1950	64	21·6	45	09·5	26	·6476	·0064	·0055
179	Admiral Rock...............	1950	63	24·6	45	10·2	176	·6284	·0003	− ·0058
180	Kennetcook.................	1945	63	43·0	45	10·4	98	·6286	− ·0072	− ·0105
181	Bramber....................	1950	64	09·2	45	10·6	65	980·6448	0·0055	0·0033
182	Goldboro....................	1944	61	39·2	45	11·1	28	·6401	− ·0034	− ·0043
183	(Arlington)..................	1950	64	25·5	45	11·7	575	·6079	·0150	− ·0046
184	Hall Harbour...............	1950	64	37·2	45	12·1	19	·6378	− ·0080	− ·0087
185	(Upper Stewiacke)..........	1950	63	00·9	45	13·0	103	·6377	− ·0015	− ·0051
186	(Middle Stewiacke)..........	1950	63	08·2	45	13·3	73	·6360	− ·0065	− ·0090
187	(Stewiacke Cross Roads).....	1950	62	56·3	45	13·7	102	·6461	·0057	·0023
188	Walton......................	1950	64	00·2	45	13·7	39	·6469	·0006	− ·0008
189	Whitehead..................	1944	61	11·3	45	14·7	8	·6484	− ·0023	− ·0026
190	Brookfield..................	1944	63	16·8	45	15·2	98	·6444	·0013	− ·0020
191	South Maitland.............	1950	63	28·2	45	15·2	30	980·6535	0·0040	0·0030
192	Melrose.....................	1950	62	02·9	45	15·7	170	·6471	·0101	·0043
193	Melrose.....................	1944	62	02·4	45	15·8	186	·6458	·0101	·0038
194	Upper Smithfield............	1950	62	11·9	45	15·9	138	·6485	·0082	·0035
195	(Tennycape)................	1950	63	52·9	45	16·0	171	·6457	·0083	·0024
196	Lower Caledonia............	1950	62	16·8	45	16·3	177	·6469	·0096	·0037
197	Caledonia...................	1950	62	23·1	45	16·7	237	·6434	·0112	·0031
198	(Eastville)..................	1950	62	53·4	45	17·0	171	·6495	·0106	·0048
199	Scotts Bay..................	1950	64	23·8	45	18·0	30	·6493	− ·0044	− ·0054
200	Aspen.......................	1950	62	03·2	45	18·1	121	·6593	·0141	·0099

PRINCIPAL FACTS FOR GRAVITY STATIONS—NOVA SCOTIA—*Continued*

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name								Free Air	Bouguer
			°	′	°	′	Ft.			
201	Densmoirs Mills	1950	63	42·2	45	18·2	35	980·6609	0·0074	0·0062
202	Hilden	1950	63	17·7	45	18·3	143	·6564	·0130	·0081
203	(Caledonia)	1950	62	24·0	45	18·9	318	·6464	·0185	·0077
204	Selmah	1950	63	32·5	45	19·1	27	·6641	·0084	·0075
205	(East Advocate)	1950	64	45·4	45	19·3	74	·6441	— ·0073	— ·0099
206	(Spencer Island)	1950	64	44·6	45	20·2	141	·6511	·0046	— ·0002
207	Canso	1944	60	59·9	45	20·5	6	·6580	— ·0016	— ·0018
208	Halfway Cove	1944	61	22·4	45	20·8	6	·6554	— ·0047	— ·0049
209	Half Island Cove	1944	61	11·3	45	21·1	96	·6507	— ·0014	— ·0046
210	(Guysborough)	1950	61	38·5	45	21·1	139	·6509	·0028	— ·0019
211	(West Advocate)	1950	64	46·9	45	21·2	33	980·6574	—0·0008	—0·0019
212	Spencer Island	1945	64	42·8	45	21·4	114	·6597	·0088	·0049
213	Truro	1950	63	16·5	45	21·8	62	·6689	·0125	·0104
214	Truro	1950	63	16·9	45	21·9	51	·6685	·0109	·0092
215	(Lansdowne)	1950	62	50·5	45	22·1	437	·6442	·0227	·0078
216	(Caledonia)	1950	62	26·5	45	22·4	620	·6328	·0280	·0069
217	(Masstown)	1950	63	26·5	45	22·8	51	·6649	·0060	·0043
218	Economy	1950	63	54·5	45	23·0	63	·6666	·0085	·0064
219	Goshen	1950	61	46·0	45	23·1	285	·6540	·0167	·0070
220	South Lochaber	1950	62	02·4	45	23·1	112	·6702	·0165	·0127
221	Upper Economy	1944	63	50·3	45	23·2	50	980·6619	0·0023	0·0006
222	Upper Economy	1950	63	50·3	45	23·3	90	·6617	·0058	·0027
223	(East Fraserville)	1950	64	39·5	45	23·7	83	·6734	·0161	·0133
224	Carr's Brook	1950	63	56·9	45	23·8	36	·6714	·0096	·0083
225	(Five Islands)	1950	64	03·3	45	23·8	70	·6604	·0018	— ·0007
226	Guysborough	1944	61	30·0	45	23·9	7	·6627	— ·0020	— ·0023
227	Glenholme	1950	63	32·0	45	23·9	56	·6607	·0006	— ·0013
228	Sunnybrae	1950	62	30·3	45	24·1	275	·6536	·0138	·0044
229	Parrsboro	1950	64	19·7	45	24·2	25	·6811	·0177	·0168
230	Portapique	1950	63	42·2	45	24·3	58	·6608	·0004	— ·0016
231	Parrsboro	1950	64	19·9	45	24·3	43	980·6799	0·0181	0·0166
232	Truro	1950	63	16·9	45	24·4	125	·6664	·0121	·0078
233	(Ward Brook)	1950	64	34·7	45	24·4	110	·6757	·0199	·0162
234	(Five Islands)	1944	64	00·2	45	24·5	457	·6406	·0173	·0018
235	Five Islands	1950	64	04·4	45	24·5	50	·6693	·0077	·0060
236	(Goshen)	1945	61	56·5	45	24·6	300	·6615	·0233	·0131
237	(Fox River)	1950	64	31·2	45	24·6	104	·6771	·0205	·0169
238	Ward Brook	1950	64	33·6	45	24·6	142	·6771	·0241	·0192
239	Glencoe	1950	62	33·2	45	24·8	232	·6597	·0148	·0069
240	Five Islands	1950	64	02·1	45	24·8	75	·6645	·0049	·0023
241	Diligent River	1950	64	27·6	45	24·8	102	980·6780	0·0209	0·0174
242	Bass River	1950	63	46·9	45	24·9	36	·6691	·0056	·0044
243	Great Village	1950	63	36·0	45	25·0	44	·6673	·0044	·0029
244	(Lower Five Islands)	1950	64	06·3	45	25·1	48	·6780	·0154	·0137
245	(Moose River)	1950	64	10·2	45	25·3	117	·6770	·0107	·0166
246	Kirkhill	1950	64	22·0	45	25·3	90	·6812	·0222	·0191
247	Lansdowne	1950	62	49·4	45	25·7	464	·6442	·0197	·0040
248	(Glenholme)	1950	63	32·0	45	25·8	122	·6655	·0087	·0046
249	Bridgeville	1950	62	36·8	45	26·1	186	·6669	·0158	·0094
250	Kemptown	1950	63	06·4	45	26·9	545	·6427	·0242	·0056

PRINCIPAL FACTS FOR GRAVITY STATIONS—NOVA SCOTIA—*Continued*

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name								Free Air	Bouguer
			°	′	°	′	Ft.			
251	(Truro)	1950	63	15·3	45	27·1	185	980·6678	0·0149	0·0086
252	(Lower Five Islands)	1950	64	06·8	45	27·1	587	·6540	·0391	·0191
253	North Lochaber	1950	62	00·8	45	27·2	116	·6734	·0139	·0100
254	(Goshen)	1950	61	55·9	45	27·3	196	·6729	·0208	·0142
255	(Glenholme)	1950	63	31·7	45	27·5	256	·6684	·0217	·0130
256	Hadleyville	1950	61	16·9	45	28·0	80	·6624	— ·0016	— ·0043
257	East Apple River	1945	64	46·1	45	28·2	55	·6711	·0045	·0026
258	Lakeland	1950	64	20·0	45	28·3	88	·6839	·0202	·0172
259	(Lansdowne)	1950	62	48·2	45	28·5	270	·6633	·0165	·0073
260	(Glenholme)	1950	63	31·9	45	29·0	412	·6691	·0349	·0208
261	(Aikens)	1950	63	32·2	45	30·0	627	980·6683	0·0528	0·0314
262	(East Mapleton)	1950	64	06·1	45	30·1	789	·6438	·0434	·0165
263	Churchville	1950	62	38·3	45	30·7	248	·6715	·0192	·0108
264	(East New Annan)	1950	63	16·1	45	31·1	595	·6594	·0393	·0190
265	Sand Point	1950	61	15·9	45	31·2	14	·6687	— ·0063	— ·0068
266	(Aikens)	1950	63	33·0	45	31·5	608	·6667	·0471	·0264
267	(Lower Mount Thom)	1950	62	58·0	45	31·6	649	·6537	·0378	·0157
268	(Five Mile Lake)	1944	61	32·9	45	31·7	469	·6516	·0186	·0026
269	(Halfway River East)	1950	64	21·1	45	31·7	46	·6874	·0146	·0131
270	(Westville)	1950	62	44·9	45	32·5	91	·6842	·0146	·0114
271	(Sand River)	1945	64	40·6	45	32·6	26	980·6754	—0·0006	—0·0014
272	(East New Annan)	1950	63	17·0	45	32·7	692	·6538	·0404	·0168
273	Folly Lake	1950	63	33·0	45	32·7	613	·6642	·0433	·0224
274	(East Mapleton)	1950	64	05·9	45	32·9	884	·6369	·0411	·0111
275	Westbrook	1950	64	18·1	45	33·0	113	·6884	·0200	·0162
276	(Antigonish)	1950	61	01·0	45	33·3	174	·6801	·0170	·0111
277	Steep Creek	1950	61	20·8	45	33·5	29	·6690	— ·0081	— ·0091
278	(South River)	1950	61	53·5	45	33·9	214	·6636	·0033	— ·0040
279	(East New Annan)	1950	63	17·9	45	34·0	815	·6484	·0445	·0167
280	(French River)	1944	62	25·5	45	34·4	137	·6806	·0124	·0077
281	(Folly Lake)	1950	63	33·3	45	34·4	313	980·6726	0·0209	0·0103
282	(Barney River)	1950	62	18·0	45	34·5	248	·6825	·0245	·0161
283	(Westville)	1950	62	44·0	45	34·6	128	·6849	·0155	·0111
284	(Greenhill)	1950	62	50·2	45	34·6	56	·6914	·0153	·0133
285	(Halfway River East)	1950	64	21·1	45	34·6	69	·6931	·0182	·0158
286	James River	1944	62	07·0	45	34·9	252	·6786	·0204	·0118
287	Mapleton	1950	64	08·9	45	34·9	264	·6782	·0211	·0122
288	New Glasgow	1950	62	38·8	45	35·0	31	·6872	·0082	·0070
289	Marshy Hope	1950	62	11·3	45	35·4	417	·6761	·0327	·0185
290	(East New Annan)	1950	63	17·4	45	35·5	635	·6650	·0419	·0203
291	East Southampton	1950	64	12·1	45	35·5	139	980·6892	0·0195	0·0148
292	Shulie River	1945	64	34·3	45	35·8	23	·6865	·0054	·0046
293	Heatherton	1944	61	47·0	45	35·9	76	·6777	·0014	— ·0011
294	Pinetree	1950	62	32·7	45	36·0	42	·6875	·0079	·0064
295	Egerton	1950	62	29·0	45	36·2	69	·6858	·0084	·0061
296	(Wentworth)	1950	63	33·8	45	36·2	202	·6831	·0182	·0113
297	Barney River	1944	62	15·3	45	36·3	205	·6875	·0228	·0158
298	Mulgrave	1950	61	23·3	45	36·4	9	·6777	— ·0057	— ·0059
299	Afton	1950	61	42·9	45	36·4	131	·6822	·0103	— ·0059
300	East New Annan	1950	63	17·1	45	36·6	450	·6769	·0348	·0195

PRINCIPAL FACTS FOR GRAVITY STATIONS—NOVA SCOTIA—*Continued*

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name		°	′	°	′	Ft.		Free Air	Bouguer
301	Port Hawkesbury	1950	61	21·8	45	36·8	8	980·6780	−0·0060	−0·0063
302	Port Hawkesbury	1950	61	21·9	45	36·9	12	·6783	− ·0055	− ·0059
303	L'Ardoise	1950	60	46·1	45	37·0	42	·6966	·0155	·0140
304	South River	1950	61	54·8	45	37·0	22	·6933	·0103	·0095
305	Grande Anse	1950	61	03·7	45	37·2	37	·6686	− ·0133	− ·0146
306	Antigonish	1950	61	58·5	45	37·6	15	·6964	·0119	·0114
307	Merigonish	1950	62	25·4	45	37·7	20	·6917	·0075	·0068
308	Tracadie	1944	61	38·4	45	37·9	41	·6914	·0089	·0075
309	(East New Annan)	1950	63	17·2	45	38·3	263	·6833	·0210	·0121
310	(Wentworth)	1950	63	33·0	45	38·5	161	·6842	·0120	·0065
311	Port Hastings	1950	61	24·0	45	38·7	7	980·6857	−0·0012	−0·0015
312	Springhill	1950	64	03·8	45	38·8	496	·6596	·0185	·0016
313	Grand River	1950	60	39·9	45	38·9	12	·7041	·0173	·0170
314	(Kempt Road)	1950	61	09·2	45	39·0	216	·6636	− ·0042	− ·0115
315	McIntyre Lake	1950	61	16·4	45	39·0	133	·6644	− ·0112	− ·0157
316	Springhill	1944	64	04·2	45	39·0	435	·6645	·0173	·0025
317	(River Hébert)	1950	64	23·0	45	39·0	28	·6947	·0092	·0083
318	(Tatamagouche)	1950	63	17·3	45	39·1	179	·6869	·0154	·0094
319	(St. Esprit)	1950	60	30·2	45	39·5	13	·7033	·0157	·0153
320	St. Peters	1950	60	52·3	45	39·5	37	·6917	·0064	·0051
321	Lyons Brook	1950	62	47·5	45	40·0	22	980·7016	0·0141	0·0133
322	Pictou	1950	62	42·3	45	40·5	11	·7027	·0133	·0130
323	Havre Bouche	1950	61	31·9	45	40·9	68	·6963	·0117	·0094
324	(Wentworth Centre)	1950	63	33·3	45	40·9	132	·6851	·0066	·0021
325	(Wentworth Centre)	1945	63	37·3	45	41·2	276	·6837	− ·0077	− ·0092
326	Springhill Junction	1950	64	06·8	45	41·5	199	·6858	·0127	·0060
327	River Hébert Station	1945	64	22·8	45	41·6	29	·6971	·0071	·0068
328	Soldier Cove	1950	60	44·2	45	41·7	24	·6996	·0098	·0089
329	Joggins	1950	64	26·9	45	41·7	107	·6886	·0066	·0029
330	Lismore	1950	62	15·7	45	42·0	58	·7037	·0166	·0146
331	Tatamagouche	1950	63	17·1	45	42·5	16	980·6994	0·0076	0·0070
332	Lower Wentworth	1950	63	33·6	45	42·6	102	·6889	·0050	·0015
333	Framboise	1950	60	22·6	45	42·9	73	·7150	·0279	·0254
334	Maccan	1945	64	14·7	45	43·0	32	·6983	·0072	·0061
335	(Lower Cove)	1950	64	26·0	45	43·0	36	·6892	− ·0015	− ·0028
336	Queensville	1950	61	21·6	45	43·2	229	·6714	− ·0015	− ·0093
337	(Stirling)	1950	60	25·2	45	43·5	179	·7058	·0279	·0208
338	(Stirling)	1950	60	26·3	45	43·5	224	·7030	·0293	·0216
339	(Antigonish Harbour)	1950	61	54·3	45	43·5	11	·7111	·0173	·0170
340	(Stirling)	1950	60	24·9	45	43·6	77	·7105	·0228	·0202
341	(Framboise)	1950	60	20·8	45	43·7	12	980·7173	0·0232	0·0229
342	(Stirling)	1950	60	25·0	45	43·8	123	·7081	·0244	·0202
343	(Stirling)	1950	60	25·6	45	43·8	186	·7035	·0258	·0194
344	(Stirling)	1950	60	26·3	45	43·8	180	·7042	·0258	·0197
345	Lower Cove	1945	64	25·8	45	43·8	85	·6822	− ·0051	− ·0080
346	(Brûlé)	1950	63	11·8	45	43·9	6	·6994	·0046	·0043
347	Oxford	1945	63	51·3	45	43·9	42	·6837	− ·0077	− ·0092
348	Stirling	1950	60	26·1	45	44·0	216	·7021	·0269	·0195
349	(Stirling)	1950	60	26·6	45	44·1	197	·7036	·0264	·0197
350	(Pictou)	1950	62	41·0	45	44·1	10	·7053	·0105	·0102

PRINCIPAL FACTS FOR GRAVITY STATIONS—NOVA SCOTIA—*Continued*

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name								Free Air	Bouguer
			°	′	°	′	Ft.			
351	(Stirling)	1950	60	26·3	45	44·4	191	980·7043	0·0260	0·0195
352	(Stirling)	1950	60	27·1	45	44·4	197	·7024	·0247	·0180
353	Craignish	1950	61	27·7	45	44·4	101	·6939	·0072	·0038
354	River John	1950	63	03·6	45	44·5	69	·6942	·0044	·0020
355	(Stirling)	1950	60	27·6	45	44·6	245	·6996	·0261	·0178
356	(Toney River)	1950	62	49·1	45	44·8	25	·7051	·0108	·0099
357	River John	1944	63	03·4	45	45·1	18	·6973	·0018	·0012
358	(Fenwick)	1950	64	11·2	45	45·8	320	·6793	·0111	·0002
359	Toney River	1950	62	53·3	45	46·1	38	·7013	·0062	·0049
360	Doctor Brook	1950	62	07·8	45	46·3	50	980·7202	0·0259	0·0242
361	Minudie	1945	64	21·0	45	46·5	85	·6893	— ·0021	— ·0050
362	(Lakevale)	1950	61	55·4	45	46·7	12	·7115	·0130	·0126
363	(Seafoam)	1950	63	01·3	45	47·2	46	·6954	— ·0007	— ·0022
364	Craigmore	1950	61	28·7	45	47·4	37	·7007	·0035	·0022
365	Fountain Road	1950	63	34·9	45	47·6	72	·6931	— ·0011	— ·0036
366	(Glendale)	1950	61	19·0	45	48·5	82	·6856	— ·0091	— ·0119
367	Georgeville	1950	62	02·0	45	48·9	249	·7133	·0338	·0253
368	Wallace	1944	63	28·4	45	48·9	11	.6939	— ·0081	— ·0084
369	Irish Cove	1950	60	39·7	45	49·4	26	·7052	·0040	·0031
370	Victoria Bridge	1950	60	17·3	45	49·5	21	980·7206	0·0187	0·0180
371	Amherst	1950	64	12·8	45	50·0	72	·6930	— ·0048	— ·0073
372	Pugwash	1944	63	39·7	45	51·0	19	·7047	·0004	— ·0003
373	Ballantyne Cove	1950	61	55·6	45	51·1	181	·7127	·0234	·0173
374	Livingstone Cove	1950	61	58·3	45	52·0	62	·7235	·0217	·0196
375	Melford	1950	61	15·4	45	52·5	58	·6962	— ·0067	— ·0087
376	Judique	1950	61	30·0	45	53·0	15	·7026	— ·0051	— ·0056
377	Head of Amherst	1950	63	56·6	45	53·4	60	·7021	— ·0020	— ·0040
378	Big Pond	1950	60	31·9	45	54·5	25	·7142	·0053	·0044
379	Rock Elm	1950	60	18·8	45	54·9	8	·7218	·0106	·0105
380	Louisburg	1950	59	57·8	45	55·5	52	980·7326	0·0247	0·0229
381	Northport	1944	63	52·2	45	56·1	6	·7061	— ·0070	— ·0072
382	Little Judique	1950	61	29·2	45	56·5	247	·6961	·0049	— ·0034
383	(Whycocomagh)	1950	61	08·5	45	56·6	7	·6941	— ·0198	— ·0201
384	Grand Narrows	1950	60	47·5	45	57·6	10	·7052	·0100	— ·0103
385	Marion Bridge	1950	60	12·8	45	58·9	20	·7291	·0130	·0123
386	Catalogne	1950	59	59·2	45	59·1	64	·7353	·0230	·0208
387	(Little Narrows)	1950	61	00·0	46	00·0	46	·7105	— ·0048	— ·0064
388	Port Hood	1950	61	31·7	46	00·2	68	·7162	·0027	·0004
389	East Bay	1950	60	23·1	46	00·8	67	·7298	·0152	·0129
390	Shenacadie	1950	60	38·7	46	01·2	14	980·7190	0·0012	—0·0016
391	Southwest Mabou	1950	61	27·1	46	01·5	37	·7151	— ·0034	— ·0046
392	(Skye Glen)	1950	61	12·4	46	02·5	186	·7168	·0109	·0045
393	(Albert Bridge)	1950	60	04·8	46	02·9	193	·7208	·0150	·0084
394	Brook Village	1950	61	18·0	46	03·1	154	·7170	·0072	·0019
395	St. Patrick Channel	1950	60	54·8	46	04·0	71	·7163	— ·0087	— ·0051
396	Beaver Cove	1950	60	33·2	46	04·1	15	·7242	·0003	— ·0008
397	Glendyer	1950	61	21·3	46	04·6	25	·7297	·0055	·0046
398	Baddeck	1950	60	43·7	46	06·4	2	·7226	— ·0065	— ·0066
399	(Hunters Mountain)	1950	60	51·7	46	07·3	229	·7237	·0146	·0068
400	Ironville	1950	60	27·6	46	08·1	32	980·7396	0·0108	0·0097

PRINCIPAL FACTS FOR GRAVITY STATIONS—NOVA SCOTIA—*Concluded*

Station			Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name		°	′	°	′	Ft.		Free Air	Bouguer
401	Beatonville..................	1950	61	19·9	46	08·1	366	·7219	·0244	·0120
402	Sydney......................	1950	60	11·7	46	08·3	46	·7361	·0083	·0067
403	Sydney......................	1950	60	11·3	46	08·4	7	·7385	·0070	·0067
404	Sydney......................	1950	60	11·9	46	08·4	37	·7371	·0083	·0070
405	Leitche Creek...............	1950	60	18·3	46	09·9	14	·7402	·0070	·0065
406	Scotsville..................	1950	61	09·4	46	11·3	208	·7266	·0096	·0024
407	Upper Middle River.........	1950	60	55·9	46	11·8	163	·7445	·0224	·0168
408	South Gut St. Ann's.........	1950	60	36·0	46	12·0	12	·7437	·0071	·0067
409	North Sydney...............	1950	60	14·8	46	12·7	41	·7434	·0085	·0071
410	Inverness...................	1950	61	18·6	46	13·9	52	980·7495	0·0138	0·0121
411	(Upper Middle River).......	1950	60	57·2	46	15·0	311	·7378	·0249	·0143
412	Dunvegan...................	1950	61	13·6	46	17·9	105	·7386	·0020	− ·0016
413	North River Bridge..........	1950	60	37·4	46	18·6	15	·7640	·0177	·0172
414	Northeast Margaree.........	1950	61	00·6	46	19·6	88	·7554	·0146	·0115
415	Margaree Forks.............	1950	61	05·9	46	20·0	20	·7525	·0047	·0040
416	Indian Brook................	1950	60	32·0	46	22·5	26	·7679	·0169	·0160
417	Margaree Harbour...........	1950	61	06·0	46	26·3	5	·7634	·0047	·0045
418	Briton Cove.................	1950	60	28·0	46	27·7	54	·7758	·0196	·0178
419	Grand Etang.................	1950	61	02·5	46	32·8	9	·7813	·0131	·0129
420	Wreck Cove..................	1950	60	24·7	46	33·1	18	980·7890	0·0213	0·0206
421	Cheticamp...................	1950	61	00·9	46	37·7	18	·7772	·0025	·0019
422	South Ingonish.............	1950	60	24·6	46	39·6	8	·7997	·0213	·0212
423	(Cap Rouge)................	1950	60	52·7	46	44·2	1,244	·7262	·0571	·0147
424	(Neil Harbour)..............	1950	60	20·2	46	46·3	16	·7890	·0013	·0007
425	Big Intervale...............	1950	60	39·3	46	49·2	1,109	·7290	·0397	·0019
426	New Haven..................	1950	60	19·4	46	49·3	5	·7922	− ·0011	− ·0013
427	Red River..................	1950	60	46·0	46	50·8	30	·7843	·0089	− ·0099
428	Cape North..................	1950	60	30·5	46	53·1	267	·7843	·0100	·0009
429	Sugar Loaf..................	1950	60	28·1	46	56·2	22	·7997	− ·0023	− ·0031
430	Bay St. Lawrence...........	1950	60	27·7	46	59·9	5	980·8086	−0·0005	−0·0007

PRINCIPAL FACTS FOR GRAVITY STATIONS—PRINCE EDWARD ISLAND

Station		Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name							Free Air	Bouguer
		°	′	°	′	Ft.			
1	(Wood Island)	62	45·1	45	58·0	45	980·7182	0·0057	0·0042
2	(Murray Harbour)	62	35·4	45	58·1	108	·7111	·0045	·0008
3	(Belle Creek)	62	51·0	45	59·9	33	·7205	·0040	·0029
4	Murray Harbour	62	31·8	46	00·3	18	·7159	− ·0026	− ·0032
5	(Belle Creek)	62	54·8	46	02·6	60	·7194	·0015	− ·0005
6	Alliston	62	36·4	46	03·5	185	·7068	− ·0008	− ·0071
7	Cambridge	62	31·6	46	04·4	78	·7117	− ·0073	− ·0099
8	Eldon	62	52·7	46	06·2	94	·7171	− ·0031	− ·0062
9	Albion	62	33·2	46	08·9	28	·7183	− ·0121	− ·0130
10	Montague	62	38·9	46	09·9	14	·7221	− ·0112	− ·0116
11	(Cherry Valley)	62	54·2	46	11·7	47	980·7248	−0·0081	−0·0096
12	Alexander	62	01·2	46	11·8	22	·7289	− ·0064	− ·0072
13	(Hampton)	63	25·0	46	12·0	90	·7364	·0072	·0041
14	New Haven	63	17·9	46	13·0	183	·7325	·0105	·0043
15	Charlottetown	63	07·5	46	13·9	11	·7389	− ·0007	− ·0010
16	Charlottetown	63	07·6	46	14·1	32	·7375	− ·0004	− ·0014
17	Tryon	63	32·6	46	14·3	7	·7446	·0041	·0038
18	(Cardigan)	62	38·4	46	14·9	131	·7221	− ·0077	− ·0122
19	Port Borden	63	42·0	46	15·2	26	·7437	·0037	·0027
20	Primrose	62	32·9	46	17·8	99	·7261	− ·0110	− ·0144
21	Brackley Station	63	08·6	46	17·9	161	980·7334	0·0020	−0·0035
22	Suffolk	63	03·1	46	18·5	62	·7384	− ·0032	− ·0053
23	Brookfield	63	17·0	46	19·5	98	·7423	·0025	− ·0008
24	(Bedeque)	63	43·4	46	19·5	19	·7462	− ·0010	− ·0017
25	Tracadie	63	57·8	46	20·8	52	·7406	− ·0054	− ·0072
26	Hunter River	63	21·0	46	21·2	81	·7449	·0010	− ·0017
27	Souris	63	15·4	46	21·4	67	·7346	− ·0109	− ·0132
28	Rollo Bay	63	20·3	46	21·5	93	·7328	− ·0105	− ·0136
29	Fredericton Station	63	25·6	46	21·5	300	·7302	·0064	− ·0038
30	Dingwell Mills	63	27·0	46	21·5	25	·7367	− ·0129	− ·0137
31	(Mount Stewart)	62	52·0	46	22·8	16	980·7426	−0·0098	−0·0103
32	Springfield	63	31·4	46	23·4	251	·7322	·0009	− ·0076
33	Summerside	63	47·5	46	23·6	30	·7499	− ·0024	− ·0034
34	(Elmira)	62	06·0	46	23·7	108	·7379	− ·0072	− ·0111
35	St. Peter's	62	34·9	46	24·9	8	·7405	− ·0158	− ·0161
36	Morell	62	42·5	46	25·0	34	·7398	− ·0143	− ·0154
37	New Annan	62	42·8	46	25·2	76	·7485	− ·0020	− ·0045
38	St. Timothy	64	03·8	46	25·2	65	·7600	·0085	·0063
39	(Rusticoville)	63	19·0	46	25·5	97	·7503	·0014	− ·0019
40	Brackley Beach	63	12·1	46	25·6	26	·7552	− ·0006	− ·0014
41	Kensington	63	38·4	46	26·2	117	980·7450	−0·0030	−0·0070
42	Elmira	62	04·0	46	26·4	119	·7447	− ·0035	− ·0075
43	(Miscouche)	63	56·0	46	26·7	24	·7607	·0032	·0023
44	(St. Margaret)	62	25·1	46	27·2	65	·7442	− ·0103	− ·0125
45	Stanley Bridge	63	27·6	46	27·8	12	·7566	− ·0037	− ·0041
46	(Elmira)	62	12·9	46	28·3	78	·7503	− ·0046	− ·0072
47	Green Gables	63	23·0	46	30·0	25	·7629	·0005	− ·0004
48	St. Philip	64	04·2	46	30·1	100	·7658	·0103	·0069
49	Richmond	63	59·5	46	30·5	71	·7676	·0088	·0063
50	(Grand River)	63	55·3	46	30·6	25	·7695	·0062	·0043

PRINCIPAL FACTS FOR GRAVITY STATIONS—PRINCE EDWARD ISLAND—*Concluded*

Station		Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name							Free Air	Bouguer
		°	′	°	′	Ft.			
51	Princetown	63	41·3	46	31·8	49	980·7616	−0·0013	−0·0029
52	Park Corner	63	33·7	46	31·9	133	·7549	− ·0002	− ·0047
53	Springhill	64	00·4	46	34·2	132	·7714	·0127	·0083
54	Port Hill	63	52·8	46	34·8	80	·7776	·0132	·0105
55	Ellerslie	63	56·8	46	36·2	53	·7812	·0121	·0103
56	(West Point)	64	21·7	46	37·6	19	·7766	·0022	·0016
57	(Milo)	64	12·5	46	38·8	80	·7762	·0057	·0030
58	(Portage)	64	04·1	46	40·1	25	·7836	·0060	·0051
59	Coleman	64	10·3	46	41·1	58	·7799	·0040	·0020
60	Cape Wolfe	64	23·7	46	43·2	62	·7785	− ·0003	− ·0024
61	St. Anthony	64	10·6	46	44·3	94	980·7813	0·0039	0·0007
62	Alberton	64	04·1	46	48·8	29	·7916	·0013	·0003
63	Roseville	64	15·5	46	49·1	54	·7904	·0020	·0002
64	(Montrose)	64	03·3	46	52·2	72	·7934	·0021	− ·0004
65	(Miminegash)	64	12·2	46	52·9	32	·7957	− ·0005	− ·0016
66	St. Louis	64	08·7	46	53·2	138	·7892	·0026	− ·0022
67	Tignish	64	02·2	46	57·1	63	·7999	·0003	− ·0018
68	(Tignish)	64	01·1	47	01·7	51	·8082	·0006	− ·0011

CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
DOMINION OBSERVATORIES

PUBLICATIONS

OF THE

Dominion Observatory

OTTAWA

Vol. XVI, No. 8

The Establishment of Primary Gravimeter Bases in Canada

BY

M. J. S. Innes and L. G. D. Thompson

EDMOND CLOUTIER, C.M.G., O.A., D.S.P.
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
OTTAWA, 1953

CONTENTS

THE ESTABLISHMENT OF PRIMARY GRAVIMETER BASES IN CANADA

BY M. J. S. INNES AND L. G. D. THOMPSON

ABSTRACT

In 1952 the Dominion Observatory initiated a program to establish throughout Canada a network of well connected primary gravimeter base stations for the control and adjustment of existing and future gravimeter surveys. A total of two hundred and seventy bases occupied during the summer forms two separate networks, one in Northern Canada and the other in Southern Ontario and Quebec.

In the course of the survey gravimeter measurements were made at all available pendulum stations and the results show that the standard deviation of most pendulum determinations is about 1·2 mgals., and that the worst errors are in the measurements made before 1936 and in those throughout the unsettled regions of Northern Canada. The comparisons provided the calibration factor for the North American gravimeter to an accuracy of one part in a thousand.

The principal facts for all the gravimeter bases and the descriptions of the sites for twenty-four principal bases in Ontario and Quebec are given. The adopted values of gravity for the bases have random errors estimated to be 0·08 mgals. and 0·15 mgals. for the southern and northern networks respectively. They may also contain systematic errors (0·5 mgals. maximum) due to the unreliability of the calibration of the gravimeter.

INTRODUCTION

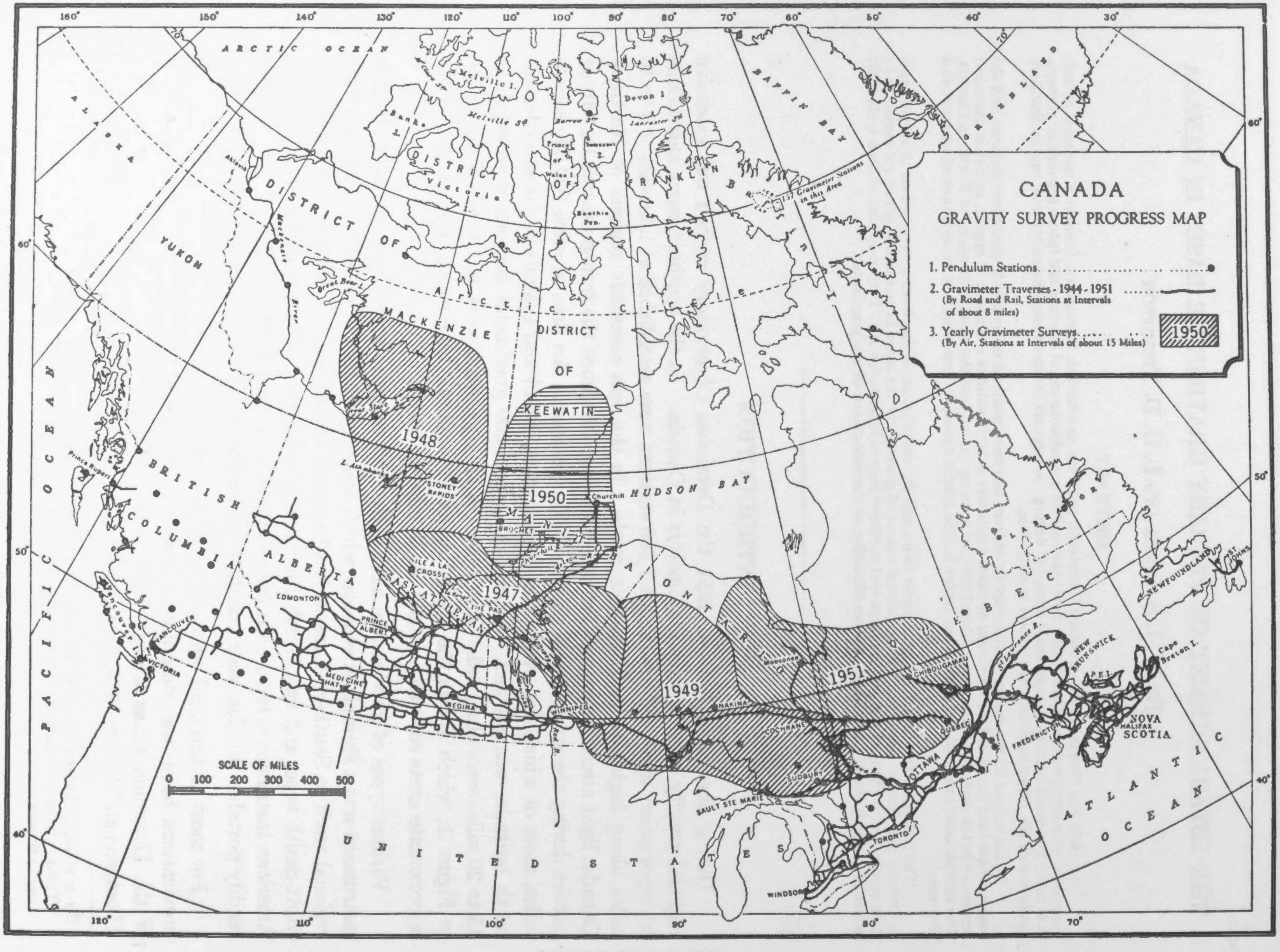
During the years 1944 to 1951 the Dominion Observatory carried out extensive regional gravity surveys with gravimeters in Canada. In the southern parts automobile transportation was used and about 7,500 stations were established at intervals of 8 to 10 miles along highways and passable roads. In the less accessible regions of Northern Canada, light aircraft equipped for water landings furnished the transportation for survey parties during the summers of 1947 to 1951, inclusive. An area of some 600,000 square miles, most of which lies within the Precambrian Shield and extends as far as 65 degrees north latitude, was covered. A total of some 1,500 gravimeter stations at intervals of 15 to 20 miles were observed. The extent of all gravimeter work in Canada is illustrated in Figure 1, which shows the more important highway traverses in the south and the approximate areas covered annually in Northern Canada.

Various types of gravimeters have been used to make the measurements. The first instrument was a Humble gravimeter which was used in 1944[1] and 1945. Since then most regional work in Southern Canada has been carried out with an Atlas instrument of the Mott-Smith type, and two North American gravimeters. For the northern work North American instruments have been used each season except 1950 and 1951 when the more readily portable Worden instruments were employed.

For most of this field work the gravity results and their geological and geophysical implications have been described in several recent publications by members of the staff of the Dominion Observatory (Saxov, 1953; Miller 1944, 1953; Garland, 1950, 1953; Thompson and Miller, 1953; Innes, 1953).

---

[1] The gravimeter became available through the courtesy of the Humble Oil and Refining Company of Houston, Texas, who own the instrument and of the American Geophysical Union, at whose disposal it had been placed by the Company.



DOMINION OBSERVATORY
DEPARTMENT OF MINES AND TECHNICAL SURVEYS

FIGURE 1.—Illustrating principal highway traverses and regions in Northern Canada where gravimeter observations have been made.

The values of gravity for each of these separate surveys have been derived, for the most part, by using calibration factors supplied by the manufacturer of the instruments. The values so obtained form consistent sets for each survey, but analysis shows differences systematic with latitude, for stations common to two or more surveys where different instruments had been employed. Re-examination of the calibration factors by comparison of the gravimeter results with pendulum station values failed to resolve the differences, because the number of pendulum stations are too few and their values of gravity too uncertain to yield a precise calibration for the range of each survey.

Consequently it was decided that these difficulties could be overcome by establishing throughout the area of the several surveys a system of primary gravimeter bases that were well connected, as well as tied to all pendulum stations including the national gravity base station in Ottawa. The greater part of the 1952 field season was therefore devoted to a program of base looping. In particular the objectives were:

(i) to establish a highly reliable network of primary gravimeter bases, suitable for the control and adjustment of previous as well as future gravimeter surveys.

(ii) to occupy all pendulum stations within the network for the purpose of adjusting the gravimeter results to the fundamental datum, and to assess the uncertainty of the pendulum station values.

(iii) to calibrate the North American gravimeter No. 85 and Worden gravimeter No. 44.

A detailed account of the results of this investigation follows.

OBSERVATIONS

Most of the results of the base looping program which forms the main subject of this report are diagramatically given in Figures 2 and 3. A total of two hundred and seventy bases were established and the work required more than 20,000 miles of automobile travel in Southern Canada and nearly 15,000 miles of air travel in the northern regions. The gravimeter bases in Southern Ontario and Quebec extend from Windsor, Ontario, in the southeast to Moosonee, Ontario to the north and to Lake Chibougamau, Quebec to the northeast (see location map). One hundred and forty-five of these bases are located in southern Ontario and are interconnected to form thirteen closed circuits (Figure 2). Not shown in this diagram are the gravimeter bases along highway traverses from North Bay, Ontario to Sault Ste. Marie, Ontario and from North Bay to Cochrane, Ontario and Rouyn, Quebec and from Montreal, Quebec to Lake Chibougamau. The southern network includes gravimeter ties to twenty-three pendulum stations, having an over-all range in gravity of 840 milligals from $g = 980 \cdot 334$ at Windsor, Ontario to $g = 981 \cdot 175$ at Moosonee, Ontario.

The northern gravimeter bases, sixty-four in all, that were connected are shown in Figure 3. They extend from Nakina, Ontario to Stoney Rapids, Saskatchewan, which is located about 1,100 miles to the northwest on Lake Athabasca. This northern network of bases forms three closed circuits, which are connected but which have no common sides. It includes observations at twelve pendulum stations for which the value of gravity varies from $g = 980 \cdot 982$ gals. at Sioux Lookout, Ontario to $g = 981 \cdot 785$ gals. at Stoney Rapids, Saskatchewan, or a range of 803 milligals.

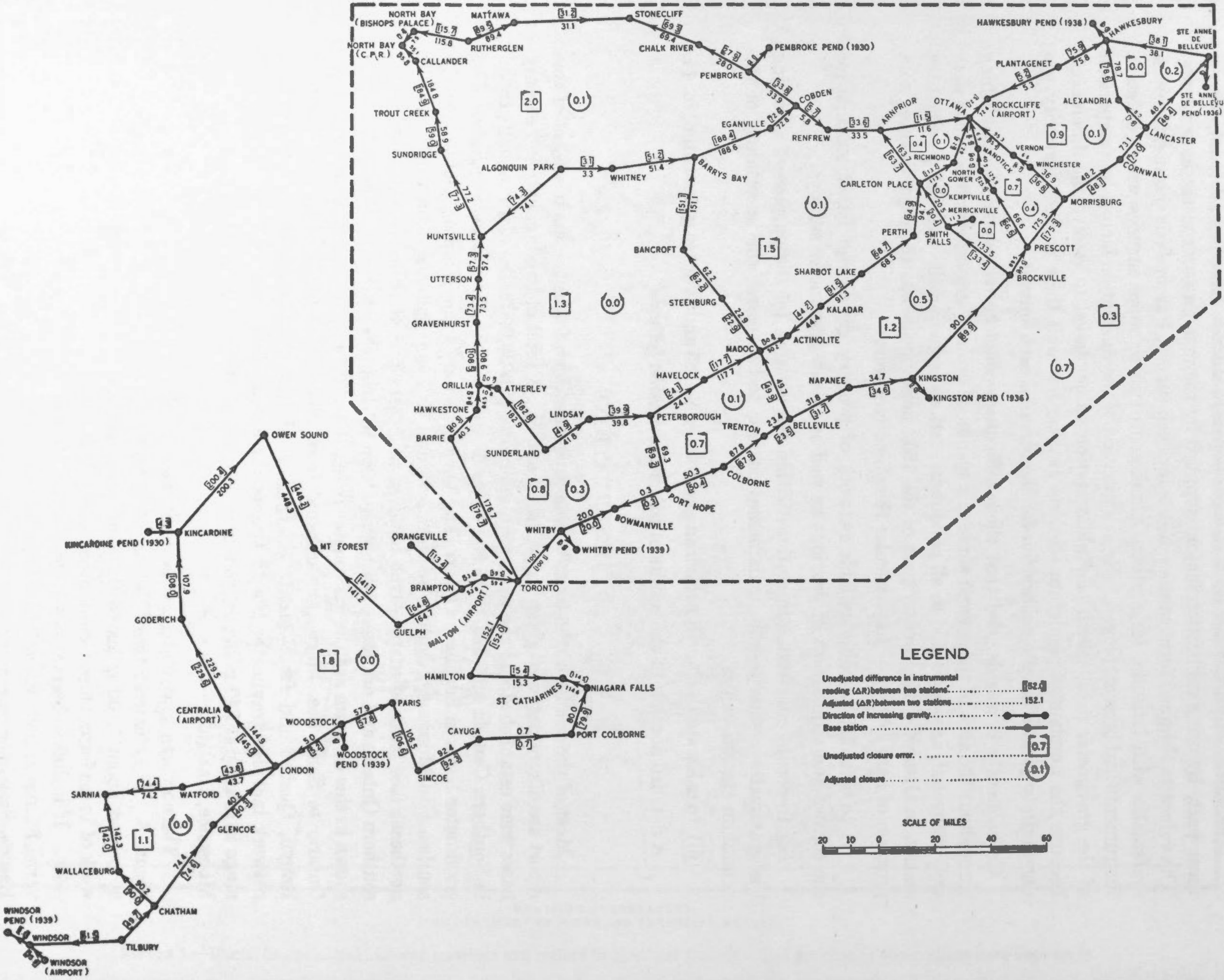


FIGURE 2.—Network of gravimeter observations in Southern Ontario.

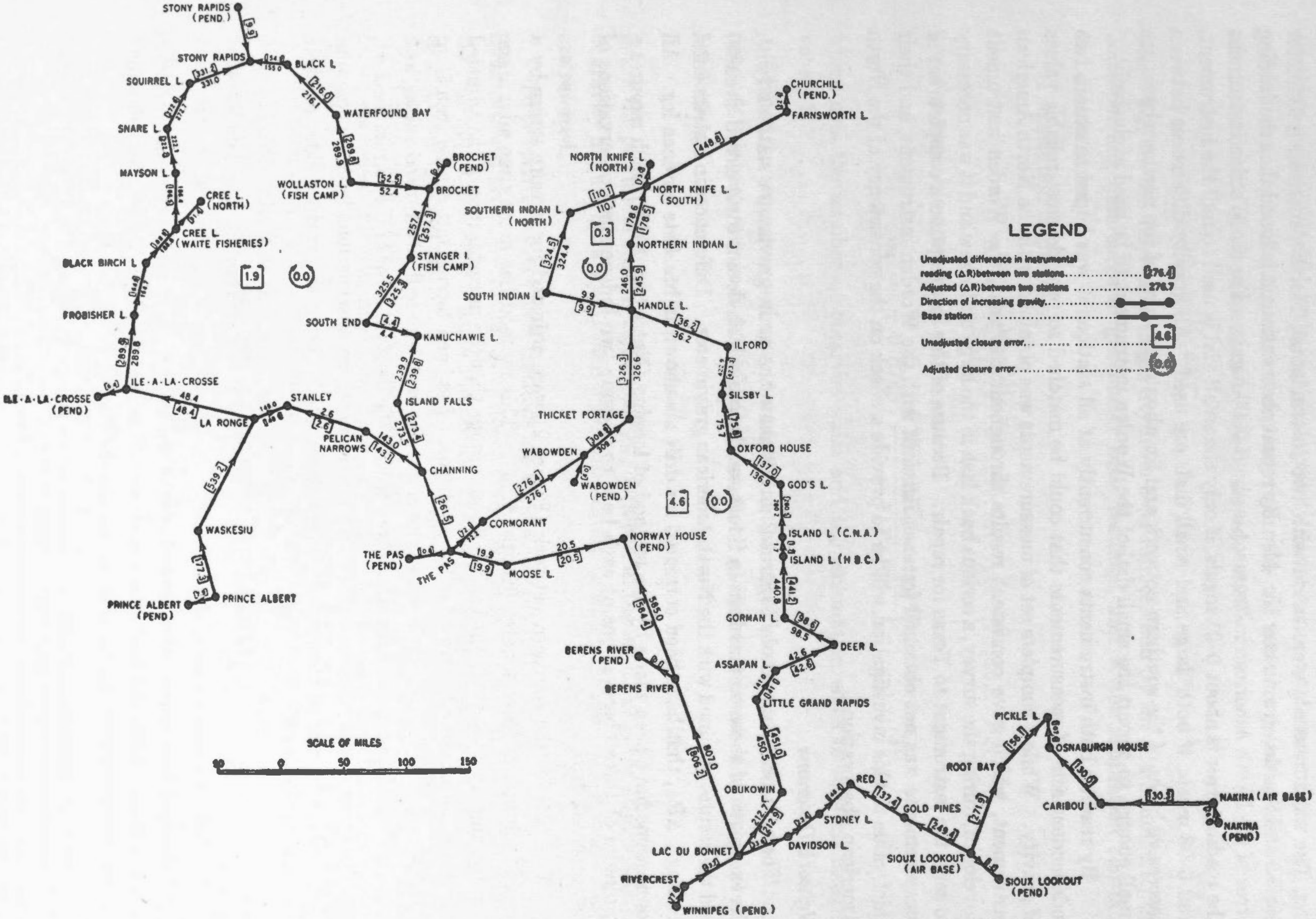


FIGURE 3.—Network of gravimeter observations in Northern Canada.

The measurements were made with two instruments[1], North American gravimeter No. 85 and Worden gravimeter No. 44. By repeat observations it is found that the reading error of the North American instrument is about 0·03 mgals. For the Worden instrument the reading error is about 0·01 mgals. if only the small dial is used to null the instrument, and 0·08 mgals. if both[2] large and small dials are used. All gravity differences between successive bases of the southern network and for about one third of the northern bases are small enough to permit the small dial of the Worden instrument to be used exclusively.

By reading both instruments concurrently at all stations it was hoped to obtain two independent sets of measurements that could be matched to provide most reliable values of gravity. While a complete set of measurements was obtained with the North American instrument, which gave consistent results throughout the year, the Worden instrument developed, during the survey, a serious back lash in the large dial screw and it was necessary to send the instrument to Texas for repair. Because of this interruption a complete set of measurements was not obtained for each network with the Worden instrument, and their chief value to this investigation will be to provide a check on the consistency of the North American observations.

Network Diagrams

The network diagrams in Figures 2 and 3 show the main gravimeter stations (with the exception of those on traverses in Southern Canada which do not form closed circuits) and the results obtained with the North American gravimeter. Differences in instrumental readings, ΔR_i, that have been corrected for drift are shown in brackets for each leg. All connections have been made by the method of looping (Nettleton, 1940) which requires a minimum of three observations at each base to provide two independent observations of instrumental drift.

The ΔR_i for the southern network (Figure 2) were adjusted for closure errors by a graphic method of least squares (Smith, 1951). This method has great time advantage over the algebraic solution, but has the disadvantage that the uncertainties of the adjusted values are not obtained. How far the adjustment has been carried out can be seen from the illustrations. The unbracketed values shown for each leg are final adjusted values, and the errors remaining in each circuit are well within the limits of error of the formal method.

The three closed circuits which comprise the northern observations have no common sides, and the errors of closure have been distributed among the various sides of their corresponding circuits.

CALIBRATION OF GRAVIMETERS

(a) North American Gravimeter No. 85

Determination of the calibration factor of the North American instrument involves the comparison of the adjusted observations with the values of gravity for the pendulum stations occupied during the process of establishing the gravimeter bases. Since the

---

[1] The North American gravimeter No. 85 has a range of about 250 milligals without resetting. The reset dial of the Worden instrument has been calibrated to provide world-wide measurements of gravity.

[2] It was found that the reading error using both dials was somewhat larger later in the season after the instrument had been altered.

southern network includes the national gravity base station in Ottawa to which both pendulum and gravimeter observations are referred[1], the relation between the two sets of measurements can be expressed by the linear equation,

$$\Delta g_i = K \cdot \Delta R_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where Δg_i are the differences in gravity from Ottawa measured by the pendulum, ΔR_i the corresponding differences in gravimeter scale readings, and K the calibration constant to be determined.

The solution is given by,

$$K = \frac{\Sigma \Delta g_i \cdot \Delta R_i}{\Sigma \Delta R_i^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

and the probable error in K is,

$$e_K = \pm 0 \cdot 6745 \left[\frac{\Sigma (K \cdot \Delta R_i - \Delta g_i)^2}{(n-1)\, \Sigma \Delta R_i^2} \right]^{\frac{1}{2}} \ldots\ldots (3)$$

where n is the number of observed pairs and the summation signs include all integral values 1, 2, ..., n.

Since the northern gravimeter network is not connected to Ottawa nor to the southern network it is necessary to include another parameter g_0 in the observation equations which are then,

$$g_i = g_0 + K \cdot \Delta R_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

g_i are the pendulum station values and g_0, obtained in the solution[2] is the adjusted value of gravity at an arbitrarily selected pendulum station to which the gravimeter observations are referred.

To be strictly correct both methods are applicable only if the ΔR_i are totally free from observational error (Worthing & Geffner, 1948) but since the weights of the individual ΔR_i are approximately the same and about 12 times the weight of a pendulum determination, a more rigorous method is not deemed necessary.

The observational data used to make two independent solutions for the calibration factor are collected in columns (1) to (5) in Tables IV and V and the results are summarized in Table I.

All pendulum station values for the respective networks were used to obtain solutions Nos. 1 and 3. The R.M.S. value of the residuals ($g - g_P$) is ± 2·54 mgals. for the southern network and ± 3·09 mgals. for the northern stations. By rejecting those stations having residuals greater than 2 mgals. (see solutions 2 and 4) the R.M.S. values of the residuals are reduced to ± 1·05 mgals. and ± 1·14 mgals. respectively. Solutions 2 and 4, therefore, yield the most probable values for K_n, or 0·23150 ± 0·00023 mgals. per div. for the southern network and 0·23179 ± 0·00026 mgals. per div. for the northern network.

---

[1] The value of gravity at Ottawa is 980·622, obtained by comparison with Potsdam (A. H. Miller, 1931).

[2] The solution is given by McCollum and Brown (1943). It is made less onerous by introducing a trial solution which approximates the linear relation sought, and then treating by least squares the differences between the observed values and the trial solution. For complete treatment, see Worthing and Geffner (1948) pp. 240–241.

TABLE I.—CALIBRATIONS OF NORTH AMERICAN GRAVIMETER No. 85

SOUTHERN NETWORK

1. Using All Pendulum Stations:

Number of Stations	22
Range in Gravity	841 mg.
Calibration Factor (K_n)	0·2315 ± 0·0002 mg/div.
Percentage Error in K_n	± 0·09
R.M.S. Residual ($g - g_p$)	± 2·54 mg.

2. Deleting Stations Nos. 4, 12, 13, 17, because of Large Residuals and No. 23 because Established Using Air Travel:

Number of Stations	17
Range in Gravity	574 mg.
Calibration Factor (K_n)	0·2315 ± 0·0002 mg/div.
Percentage Error in K_n	± 0·09
R.M.S. Residual ($g - g_p$)	± 1·05 mg.

NORTHERN NETWORK

3. Using All Pendulum Stations:

Number of Stations	12
Range in Gravity	803 mg.
Calibration Factor (K_n)	0·2315 ± 0·0005 mg/div.
Percentage Error in K_n)	± 0·21
Error in g_0	± 1·03 mg.
R.M.S. Residual ($g - g_p$)	± 3.09 mg.

4. Deleting Stations Nos. 4, 5, 6, 7, 12, because of Large Residuals:

Number of Stations	7
Range in Gravity	788 mg.
Calibration Factor (K_n)	0·2318 ± 0·0003 mg/div.
Percentage Error in K_n)	± 0·11
Error in g_0	± 0·51 mg.
R.M.S. Residual ($g - g_p$)	± 1·14 mg.

These two values hardly differ significantly, and since there is no information[1] in the results to show which is the better calibration it might seem best to adopt the mean value for both networks. However, since the northern network consists only of three circuits, none of which have common sides to facilitate the elimination of possible cumulative error in the ΔR_i, the value obtained for the southern network (0·2315 mg. per div.) has been adopted for all observations taken with the North American gravimeter in 1952. This value is 1·3 per cent smaller than the value supplied by the manufacturer in 1948.

(b) The Calibration Factor of North American No. 85 during the Seasons of 1948 and 1949

As a considerable number of the 1952 gravimeter bases were occupied with the North American instrument during the surveys of 1948 and 1949, it is now possible to determine the calibration factor of the instrument for these years by comparison with the values of gravity based upon the 1952 calibration. Comparisons over gravity differences totalling about 350 milligals give the following calibration factors,

1948	0·2326 ± 0·0001 mgals. per div.
1949	0·2341 ± 0·0003 mgals. per div.

---

[1] The error of the calibration factor varies directly with the errors of the pendulum measurements, and inversely with the range in gravity and the square root of the number of stations. Both solutions 2 and 4 give about the same accuracy for K_n or ± 0·1 per cent, because the smaller number of stations used in solution 4 is offset by their larger range in gravity, while the errors in the pendulum station values are approximately the same magnitude for both networks.

These differences are unexpectedly large and differ significantly from each other and from the value obtained for the calibration factor from the 1952 measurements (0·2315 mgals. per div.). No satisfactory explanation can be given to account for the different results which suggests an increase in the calibration factor for 1949 and a decrease since that time. The instrument gave satisfactory service each year and although the time between base readings was somewhat longer than in 1952, the changes are too large to be due to poorer base control. Nor does it seem that non-linearity of the instrument can account for the apparent change in the calibration since no significant change in the constant was found over the same latitudes in 1952.

(c) Worden Gravimeter No. 44

The breakdown of the Worden instrument during the field season, which also resulted in an alteration of the calibration factor while being repaired, did not permit a sufficient number of observations to be taken for an independent calibration against pendulum station values. Consequently an alternate least square method (McCollum and Browne, 1943) based upon comparative readings with the North American gravimeter, has been followed. The relative calibrations are based upon the adopted value of K = 0·2315 mgals. per division for the North American instrument and the results are given in Table II.

TABLE II.—THE CALIBRATION OF WORDEN GRAVIMETER No. 44

	Small Dial		*Large Dial*
First Calibration	Southern Network	Northern Network	Northern Network
Transportation	Automobile	Aircraft	Aircraft
Number of Comparisons	51	30	17
Average Gravity Interval	19 mgal.	25 mgal.	55 mgal.
Matching Factor	0·4814	0·4808	3·036
Percentage Error	± 0.04	±0.07	± 0·09
R.M.S. Residuals	± 0·11 mgal.	±0·17 mgal.	± 0·30 mgal.
Calibration Factor (mgals. per division)	0·1115	0·1113	7·028

—	*Small Dial*	*Large Dial*
Second Calibration	Southern Network	Northern Ontario
Transportation	Automobile	Aircraft
Number of Comparisons	45	4
Average Gravity Interval	17 mgal.	105 mgal.
Matching Factor	0·4825	3·195
Percentage Error	± 0·05	± 0·05
R.M.S. Residuals	± 0·11 mgal.	± 0·22 mgal.
Calibration Factor (mgals. per division)	0·1117	7·396

Observations from both networks provided the data for the first calibration. The two solutions for the small dial calibration do not differ significantly and their weighted mean value, 0·1114 mgals. per scale division, has been adopted as the best value for the first part of the season. The corresponding large dial constant depends upon 17 comparisons made over a 500 milligal range in the western circuit of the northern network. Because of the failure of the instrument, the observations of the other circuits are too uncertain to be used in the reduction. The best value for the calibration of the large dial is, therefore, 7·028 mgals. per scale division. The constants supplied by the manufacturer are both 0·3 per cent greater, or 0·1117 and 7·047 mgals. per division, respectively.

The second part of the table gives the statistics of the calibration after the instrument was repaired in mid-season. Comparisons made over forty-five gravity differences in the southern network were used for the small dial calibration. The calibration of the large dial depends on four comparisons made in Northern Ontario using aircraft transportation. Although more comparisons using the large dial are desirable, the gravity intervals of each comparison are quite large and the calibrations of both dials appear to be equally reliable; both solutions show that the Worden measurements have been matched with the North American observations to one part in two thousand. The absolute error in adopted constants depends, of course, on the accuracy of the constant adopted for the North American instrument (± 0·1 per cent).

The constants adopted for this calibration of the Worden are:

Small dial — 0·1117 mgals. per div.
Large dial — 7·396 mgals. per div.

These factors are about 0·3 per cent smaller than those supplied by the manufacturer.

THE ACCURACY OF THE GRAVITY DIFFERENCES

The accuracy of the gravity differences between successive stations in the networks depends upon how accurately the drift has been estimated in reducing the primary observations, and how well the calibration factor of the gravimeters have been determined.

The standard deviation σ, of a difference in gravity as measured by each instrument is given in Table III. The deviations have been estimated by two methods,

(i) from the residuals of the primary observations (at least two residuals for each gravity difference)

(ii) from the closure errors of the networks using the following equation[1],

$$\sigma^2 = \frac{1}{m} \sum_{i=1}^{i=m} \frac{\epsilon_i^2}{n} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

ϵ_i is the closure error of the i^{th} circuit, n the number of gravity differences forming the circuit and m is the number of circuits in the network.

TABLE III.—STANDARD ERROR OF GRAVITY DIFFERENCES

	From Residuals	*From Closure Errors*
A. SOUTHERN CANADA (AUTOMOBILE TRANSPORTATION)		
(i) North American Gravimeter	± 0·03 mgals.	± 0·08 mgals.
(ii) Worden Gravimeter (small dial only)	± 0·02 mgals.	± 0·06 mgals.
B. NORTHERN CANADA (AIRCRAFT TRANSPORTATION)		
(i) North American Gravimeter	± 0·08 mgals.	± 0·15 mgals.
(ii) Worden Gravimeter (both dials)	± 0·08 mgals.	± 0·12 mgals.

Both methods of reduction show that the errors in the gravity differences of the northern network are nearly twice as large as those estimated for the southern observations.

---

[1] See McCollum and Brown (1943) also Cook (1951)

The larger deviation of the Worden measurements can be attributed to the larger reading error of the instrument when the high range dial is used, as was necessary for a large number of the observations in the northern network. The greater error in the measurements made with the North American instrument, on the other hand, can be accounted for by the variable drift rates observed for a portion of the work in Northern Canada. At first it was thought the erratic behaviour of the instrument might be related to the mode of transportation, but it has since been found due to a faulty reset mechanism which introduced small tares in the readings. It is believed that most of the error from this cause is confined to the several legs of the network where the gravity differences are larger than usual.

The standard deviations estimated from the closure errors of the networks are, for both instruments, considerably larger than those estimated from the residuals. Although the reason for this is not clearly understood, and requires further investigation, there is some confirmation from the results of the relative calibrations that the closure errors provide the more reliable estimates of the deviations. In Table II the residuals, whose root mean square values have been computed for each solution, are the differences between the values obtained by the separate instruments for the various gravity differences over which the instruments were compared. Since the measurements with each instrument are independent, the sum of the squares of the standard deviation for each should be equal to the sum of the squares of the residuals that are defined above, or,

$$(\sigma_N^2 + \sigma_w^2)^{\frac{1}{2}} = \text{Root Mean Square of the Residuals,}$$

where σ_N and σ_w are the standard deviations of the North American and Worden gravimeters, respectively. Substituting the values for σ_N and σ_w for the southern network from Table III gives,

$$[(0\cdot08)^2 + (0\cdot06)^2]^{\frac{1}{2}} = \pm 0\cdot10 \text{ mgal.,}$$

which is in good agreement with ± 0·11 mgal., the value obtained for the root mean square of the residuals for both calibrations of the small dial using observations from the southern network.

Substitution of the deviations of the two instruments for the northern network gives

$$[(0\cdot15)^2 + (0\cdot12)]^{\frac{1}{2}} = \pm 0\cdot19 \text{ mgals.}$$

This value is intermediate to the value of the root mean square of the residuals from the small dial calibration (± 0·17 mgals.) and from the large dial calibration (± 0·30 mgals). The agreement is as good as might be expected when it is considered that the standard deviation from the closure errors of the Worden measurements is based upon observations using both the high range and low range dials.

The main conclusions to be drawn from these calculations are,

(i) the closure errors of the networks provide the most reliable estimates for the standard deviation of the gravity differences.

(ii) the residuals of the comparative observations have a random distribution and sufficient comparisons have been made to provide a reliable calibration of the Worden instrument in terms of the constant adopted for the North American gravimeter.

In addition to the random errors of observations that have just been discussed, the gravity differences and, of course, the adopted values of gravity for the bases are subject to cumulative error arising from the uncertainty in the calibration of the gravimeter. This has been found to be about ± 0·1 per cent for the North American calibration and, therefore, the gravity values for the base stations may have systematic errors varying from 0 to ± 0·5 milligals, with the outlying stations of each network having the larger error.

THE ADJUSTED VALUES OF GRAVITY

(a) Pendulum Stations

The most probable values of gravity for the pendulum stations are those derived from the gravimeter observations using the adopted value for K_N ; they are listed in column (7) of Tables IV and V. The differences $(g - g_P)$ are given in column (8) and include errors of the gravimeter observations as well as those of the pendulum determinations. The standard deviation of the gravimeter observations have been estimated to be less than 0·1 milligals and it is likely, therefore, that each difference $(g - g_P)$ is dominated by the error in the corresponding pendulum measurement. The root mean square of the differences[1] therefore, may be taken as a good value for the standard deviation of the pendulum observations.

---

[1] Should the gravimeter values of gravity contain systematic errors resulting from the unreliability of the calibration factor, the R.M.S. of the true differences would be correspondingly larger.

TABLE IV.—ADJUSTMENT OF PENDULUM STATION VALUES OF GRAVITY

(Eastern Network

	(1)	(2) Year Established	(3) g_p	(4) Δg_i(mg.)	(5) ΔR_i	(6) $K\cdot\Delta R_i$(mg.)	(7) g	(8) $g - g_p$(mg.)
1	Windsor, Ont.	1939	980·334	−288	−1239·4	−286·92	980·33508	+1·08
2	Woodstock, Ont.	1939	.357	−265	−1141·5	−264·26	·35774	+0·74
3	Whitby, Ont.	1939	.469	−153	− 665·0	−153·95	·46805	−0·95
4	Kincardine, Ont.	1930	.476	−146	− 660·1	−152·81	·46919	−6·81
5	Kingston, Ont.	1936	·524	− 98	− 419·3	− 97·07	·52493	+0·93
6	Ottawa, Ont.		·622	0	0	0	·62200	0·00
7	Pembroke, Ont.	1930	·634	+ 12	+ 54·1	+ 12·52	·63452	+0·52
8	Ste. Anne de Bellevue, Que.	1936	·645	+ 23	+ 105·1	+ 24·33	·64633	+1·33
9	Montreal, Que.	1936	·650	+ 28	+ 125·1	+ 28·96	·65096	+0·96
10	Hawkesbury, Que.	1938	·657	+ 35	+ 142·9	+ 33·08	·65508	−1·92
11	St. Jerome, Que.	1939	·661	+ 39	+ 170·9	+ 39·56	·66156	+0·56
12	Sault Ste. Marie, Ont.	1939	·682	+ 60	+ 271·0	+ 62·74	·68474	+2·74
13	Sudbury, Ont.	1936	·683	+ 61	+ 276·3	+ 63·96	·68596	+2·96
14	Quebec, Que.	1937	·728	+106	+ 462·4	+107·05	·72905	+1·05
15	Stoneham, Que.	1938	·752	+130	+ 565·5	+130·91	·75291	+0·91
16	Portneuf, Que.	1939	·754	+132	+ 567·6	+131·40	·75340	−0·60
17	La Tuque, Que.	1930	·783	+161	+ 661·9	+153·23	·77523	−7·77
18	New Liskeard, Ont.	1936	·785	+163	+ 712·6	+164·97	·78697	+1·97
19	Roberval, Que.	1939	·858	+236	+1024·3	+237·13	·85913	+1·13
20	Chicoutimi, Que.	1938	·866	+244	+1051·4	+243·40	·86540	−0·60
21	Tadoussac, Que.	1938	·880	+258	+1112·0	+257·43	·87943	−0·57
22	Cochrane, Ont.	1946	·888	+266	+1147·1	+265·55	·88755	−0·45
23	Moosonee, Ont.	1946	981·175	+553	+2394·5	+554·33	981·17633	+1·33

TABLE V.—ADJUSTMENT OF PENDULUM STATION VALUES OF GRAVITY

(Northern Network)

	(1) Pendulum Station	(2) Year Established	(3) g_P	(4) Δg(mg.)	(5) ΔR_i	(6) $K\cdot\Delta R_i$(mg.)	(7) g	(8) $g - g_P$(mg.)
1	Nakina, Ont.	1927	980·987	0	0	0	980·98885	+1·85
2	Sioux Lookout, Ont.	1927	·982	− 5	− 32·4	− 7·50	·98135	−0·65
3	Winnipeg, Man.	1946	·994	+ 7	+ 26·3	+ 6·09	·99494	+0·94
4	Berens River, Man.	1927	981·203	+216	+ 954·9	+221·06	981·20991	+6·91
5	Prince Albert, Sask.	1924	·236	+249	+1048·9	+242·82	·23167	−4·33
6	The Pas, Man.	1946	·341	+354	+1510·2	+349·61	·33846	−2·54
7	Norway House, Man.	1927	·349	+362	+1539·8	+356·46	·34531	−3·69
8	Ile a la Crosse, Sask.	1946	·409	+422	+1812·3	+419·55	·40840	−0·60
9	Wabowden, Man.	1946	·416	+429	+1844·3	+426·96	·41581	−0·19
10	Brochet, Man.	1946	·651	+664	+2852·4	+660·33	·64918	−1·82
11	Churchill, Man.	1946	·770	+783	+3379·9	+782·45	·77130	+1·30
12	Stoney Rapids, Sask.	1946	·785	+798	+3451·5	+799·02	·78787	+2·87

Generally the errors are about what we have been led to expect from repeated pendulum measurements. The worst errors are found in the earlier observations and in those obtained in the unsettled regions of Northern Canada[1]. The R.M.S. difference for all thirty-four pendulum stations is ± 2·70 mgals. For the twelve stations that are in Northern Canada the R.M.S. difference is ± 2·91 milligals, while for the twenty stations established in Southern Canada since 1936, it is ± 1·15 mgal.

It might also be pointed out that the signs of the differences ($g - g_P$) are, to some extent, systematic with the years of observation. All differences for the five 1936 stations are positive, the differences for three of the four 1938 stations are negative, while five of the seven stations established during 1939 have positive differences.

The density of the pendulum stations throughout the areas of the two gravimeter networks is probably greater than it is in other areas of Canada of comparable size. Although it has been shown that the better of these determinations are sufficient to prevent serious error in the gravimeter results, there is still much to be desired and new and more precise pendulum measurements are needed before the calibration of the gravimeters can be improved and better values of gravity derived. The greatest need is, of course, for new stations to be established throughout the large areas of Northern Canada, where so far only a few scattered measurements have been made.

(b) Gravimeter Bases

The principal facts for all gravimeter bases established during 1952 have been collected in Table VI. The data for the bases in the southern network have been tabulated in separate groups for each of the provinces of Ontario and Quebec. They are listed, for the most part, in order of increasing latitude and according to the number of the provincial highway on which they are located. The bases of the northern network have been divided into several north-south lines and tabulated generally in the order of increasing gravity.

---

[1] Earlier measurements have larger errors due to inconstancy of pendulum periods (see A. H. Miller, 1936). In Northern Canada the larger errors can be attributed to more poorly temperature controlled sites for the observations.

TABLE VI.—PRINCIPAL FACTS FOR GRAVIMETER BASES

A. SOUTHERN NETWORK

(1) ONTARIO

Station Name	Longitude		Latitude		Elevation (Feet)	Observed Gravity
	°	′	°	′		
Bases along Highway No. 2						
Windsor	83	02·4	42	19·1	588	980·3347
Windsor Airport	82	58·1	42	16·2	623	·3264
Tilbury	82	25·9	42	15·6	587	·3205
Chatham	82	10·9	42	24·4	594	·3320
Glencoe (Hwy. 80)	81	42·7	42	44·9	728	·3492
London	81	15·1	42	59·0	814	·3585
Woodstock	80	45·5	43	07·8	990	·3574
Paris	80	23·2	43	11·9	829	·3708
Hamilton	79	52·2	43	15·5	316	·4092
Toronto	79	23·5	43	40·0	370	·4444
Whitby	78	56·6	43	52·7	310	·4676
Bowmanville	78	41·4	43	54·9	365	·4722
Port Hope	78	17·2	43	57·0	298	·4721
Colborne	77	58·6	44	00·8	361	·4838
Trenton	77	34·8	44	06·5	257	·5041
Belleville	77	22·8	44	09·7	260	·5095
Napanee	76	57·3	44	15·2	315	·5169
Kingston	76	28·9	44	13·7	254	·5249
Brockville	75	41·3	44	35·4	310	·5457
Prescott	75	31·5	44	42·8	311	·5665
Morrisburg	75	11·3	44	53·9	270	·6070
Cornwall	74	44·0	45	01·9	193	·6181
Lancaster	74	30·2	45	08·4	164	·6350
Bases along Highway No. 3						
Simcoe	80	18·7	42	50·3	714	980·3461
Cayuga	79	51·8	42	56·9	600	·3675
Port Colborne	79	15·1	42	53·3	583	·3677
Bases along Highway No. 4						
Centralia Airport	81	30·2	43	17·5	813	980·3920
Bases along Highway No. 6						
Mt. Forest	80	44·8	43	58·6	1353	980·4127
Owen Sound	80	56·7	44	34·0	600	·5165
Bases along Highway No. 7						
Guelph	80	14·7	43	32·8	1042	980·3801
Brampton	79	45·9	43	41·2	715	·4182
Malton Airport	79	38·1	43	41·6	565	·4306
Sunderland	79	03·7	44	16·0	859	·4694
Lindsay	78	44·5	44	21·2	847	·4791
Peterborough	78	19·3	44	18·5	673	·4883
Havelock	77	52·9	44	26·0	700	·4939
Madoc	77	29·1	44	30·4	575	·5211
Actinolite	77	19·2	44	33·2	555	·5328
Kaladar	77	07·0	44	38·7	705	·5225
Sharbot Lake	76	41·3	44	46·4	650	·5436
Perth	76	15·0	44	53·9	439	·5595
Bases along Highway No. 8						
Niagara Falls	79	04·8	43	05·6	606	980·3862
St. Catharines	79	14·5	43	09·7	369	·4127

TABLE VI.—PRINCIPAL FACTS FOR GRAVIMETER BASES—*Continued*

A. SOUTHERN NETWORK—*Continued*

(1) ONTARIO—*Continued*

Station Name	Longitude	Latitude	Elevation (Feet)	Observed Gravity
	° ′	° ′		
Bases along Highway No. 10				
Orangeville	80 05·4	43 54·8	1397	980·3919
Bases along Highway No. 11				
Barrie	79 41·3	44 23·3	727	980·4854
Hawkestone	79 28·5	44 30·0	780	·4947
Orillia	79 24·7	44 36·5	723	·5143
Atherley (Hwy. No. 12)	79 21·8	44 36·2	738	·5118
Gravenhurst	79 22·3	44 55·2	832	980·5394
Utterson	79 19·7	45 12·7	1036	·5564
Huntsville	79 12·9	45 19·3	959	·5697
Sundridge	79 23·9	45 46·0	1100	·5876
Trout Creek	79 21·5	45 59·2	1027	·6012
Callander	79 22·0	46 13·3	670	·6440
North Bay (C.P.R.)	79 27·9	46 18·6	622	·6568
North Bay (Bishop's Palace)	79 28·0	46 18·9	677	·6550
Junc. Hwys. 11 and 64	79 49·9	46 43·1	965	·6849
Timagami	79 47·0	47 03·9	986	·7250
New Liskeard	79 40·3	47 30·6	620	·7863
Englehart	79 52·1	47 49·5	679	·8268
Rock Outcrop (Rd. to Round L.)	80 00·8	48 00·8	979	·7907
Swastika	80 06·0	48 06·4	1006	·8065
Ramore	80 19·3	48 26·3	944	·8586
Matheson	80 28·2	48 32·2	860	·8588
Porquis	80 46·8	48 42·4	944	·8729
Porquis Airport	80 47·1	48 44·4	1002	·8732
Cochrane	81 00·6	49 03·6	917	·8874
Bases along Highway No. 15				
Merrickville	75 50·5	44 55·3	357	980·5793
Smith Falls	76 01·0	44 54·2	428	·5767
Carleton Place	76 08·4	45 08·2	453	·5814
Richmond	75 49·5	45 11·0	310	·6076
Bases along Highway No. 16				
Kemptville	75 38·6	45 00·8	319	980·5819
North Gower	75 43·1	45 07·9	300	·6110
Manotick	75 41·1	45 13·6	275	·6204
Bases along Highway No. 17				
Hawkesbury	74 36·3	45 36·6	147	980·6551
Plantagenet	74 59·0	45 31·0	168	·6375
Rockcliffe Airport	75 38·3	45 27·4	178	·6388
Ottawa	75 42·9	45 23·6	274·3	·6220
Arnprior	76 21·4	45 25·9	299	·6193
Renfrew	76 41·5	45 28·1	422	·6271
Cobden	76 53·1	45 37·6	476	·6257
Pembroke	77 07·3	45 49·4	410	·6336
Chalk River	77 27·1	46 01·1	522	·6401
Stonecliff	77 53·7	46 12·8	562	·6561
Mattawa	78 42·3	46 18·7	563	·6489
Rutherglen	79 02·3	46 16·2	789	·6282
Sturgeon Falls	79 55·7	46 22·0	688	·6742

TABLE VI.—PRINCIPAL FACTS FOR GRAVIMETER BASES—*Continued*

A. SOUTHERN NETWORK—*Continued*

(1) ONTARIO—*Concluded*

Station Name	Longitude	Latitude	Elevation (Feet)	Observed Gravity
	° ′	° ′		
Bases along Highway No. 17—Concluded				
Hagar	80 25·0	46 27·3	691	·7026
Sudbury	81 00·0	46 29·8	881	·6860
Worthington	81 27·1	46 22·9	775	·6861
Espanola	81 46·0	46 16·1	672	·6742
Webbwood	81 52·7	46 16·0	661	·6761
Spanish	82 21·0	46 11·6	610	·6575
Blind River	82 57·4	46 10·8	602	·6493
Iron Bridge	83 13·3	46 16·7	619	·6542
Bruce Station	83 45·7	46 19·0	680	·6652
Sault Ste. Marie	84 19·6	46 30·5	600	·6841
Bases along Highway No. 21				
Goderich	81 42·7	43 44·6	718	980·4452
Kincardine	81 38·2	44 10·5	649	·4702
Bases along Highway No. 22				
Watford	81 52·5	42 57·1	796	980·3686
Bases along Highway No. 31				
Winchester	75 20·8	45 04·9	250	980·5984
Vernon	75 27·9	45 09·9	289	·5999
Bases along Highway No. 34				
Alexandria	74 38·3	45 19·0	257	980·6369
Bases along Highway No. 40				
Wallaceburg	82 22·5	42 35·2	584	980·3529
Sarnia	82 24·4	42 58·1	599	·3858
Bases along Highway No. 60				
Algonquin Park	78 35·7	45 33·1	1419	980·5526
Whitney	78 14·0	45 29·8	1266	·5533
Barry's Bay	77 40·5	45 29·5	984	·5652
Eganville	77 06·1	45 32·4	551	·6089
Bases along Highway No. 62				
Steenburg	77 39·2	44 50·5	No elevation	980·5158
Bancroft	77 51·6	45 03·5	1085	·5302
Bases along Highway No. 66				
Kirkland Lake	80 01·9	48 09·2	1048	980·8060
Larder Lake	79 42·8	48 05·8	948	·8104
Bases along Highway No. 67				
South Porcupine	81 12·4	48 28·7	920	980·8342

(2) QUEBEC

Bases along Highway No. 2				
Ste.-Anne-de-Bellevue	73 56·6	45 24·5	110	980·6463
Dorval Airport	73 45·5	45 27·3	97	·6454
Montreal	73 34·0	45 30·0	151	·6499
Pointe-aux Trembles	73 29·5	45 38·4	42	·6581

TABLE VI.—PRINCIPAL FACTS FOR GRAVIMETER BASES—*Continued*

A. SOUTHERN NETWORK—*Concluded*

(2) QUEBEC—*Concluded*

Station Name	Longitude		Latitude		Elevation (Feet)	Observed Gravity
	°	′	°	′		
Bases along Highway No. 2—Concluded						
St. Sulpice	73	21·2	45	49·6	35	·6786
Berthierville	73	10·7	46	05·0	29	·6880
Trois Rivieres	72	32·3	46	20·6	49	·7111
Cap-de-la-Madeleine	72	30·0	46	22·4	55	·7145
St.-Anne-de-la-Perade	72	12·2	46	34·6	38	·7428
Portneuf	71	53·0	46	41·7	19	·7530
Quebec	71	13·2	46	48·2	340	·7289
Levis	71	11·0	46	48·8	17	·7486
Montmagny	70	33·1	46	58·8	51	·7487
Ste.-Anne-de-la-Pocatiere	70	01·4	47	22·1	154	·7818
Notre-Dame-du-Portage	69	37·1	47	45·8	34	·8318
Riviere-du-Loup	69	31·7	47	49·6	290	·8232
Bases along Highway No. 15						
St. Simeon	69	53·0	47	50·7	25	980·8584
Tadoussac	69	42·7	48	08·2	10	·8816
Bases along Highway No. 16						
Petit Saquenay	70	04·2	48	12·9	58	980·8804
Grande Baie	70	51·0	48	19·1	18	·8713
Chicoutimi	71	03·8	48	25·7	75	·8648
Bases along Highway No. 19						
Grand-Mere	72	41·2	46	36·9	426	980·7191
Ste. Tite	72	33·9	46	43·4	457	·7316
St.-Roche-de-Mekinac	72	46·3	46	48·9	478(altimeter)	·7257
Riviere-aux-Rats	72	53·6	47	12·6	393(altimeter)	·7585
Lac-a-Beauce	72	46·0	47	19·3	689(altimeter)	·7650
La Tuque	72	47·0	47	26·3	545	·7750
Bases along Highway No. 41						
Lachute	74	20·0	45	39·4	226	980·6470
St. Jerome	74	00·2	45	46·8	310	·6609
St. Jacques	73	34·3	45	56·9	196	·6797
Joliette	73	26·2	46	01·3	186	·6906
Base along Highway No. 54						
Stoneham	71	23·5	46	57·6	511	980·7518
Bases along Highway No. 55						
St.-Joseph-d'Alma	71	39·4	48	33·0	302	980·8650
Roberval	72	12·6	48	30·7	346	·8587
St. Felicien	72	26·4	48	39·0	367	·8658
Bases along Highway No. 59						
Arntfield	79	15·3	48	12·1	935	980·8166
Rouyn	79	01·9	48	14·4	962	·8267
Cache Lake	74	25·6	49	49·6	1245(altimeter)	980·9440

TABLE VI.—PRINCIPAL FACTS FOR GRAVIMETER BASES—*Continued*

B. NORTHERN NETWORK

Station Name	Longitude		Latitude		Elevation (Feet)	Observed Gravity
	°	′	°	′		
Nakina (air)	86	42·5	50	13·1	973 B	980·9950
Caribou Lake	89	09·3	50	22·7	1172 B	981·0251
Osnaburgh House	90	15·8	51	08·4	1239 C	·0552
Pickle Lake	90	11·9	51	32·7	1183 C	·0802
Root Bay	91	22·6	50	55·7	1238 C	·0440
Sioux Lookout (air)	91	55·4	50	05·7	1176 B	980·9811
Gold Pines	93	10·6	50	38·4	1184 B	981·0388
Red Lake	93	49·2	51	01·6	1165 C	·0706
Sydney Lake	94	27·6	50	39·9	1166 C	·0363
Davidson Lake	95	09·4	50	26·8	1108 B	·0309
Lac du Bonnet	96	03·5	50	15·6	824 B	·0231
Rivercrest	97	02·5	50	00·0		·0130
Obukowin Lake	95	11·9	51	04·3	1067 B	·0723
Little Grand Rapids	95	27·6	52	02·6	983 B	·1766
Assapan Lake	95	10·1	52	26·1	1030 B	·2092
Deer Lake	94	01·3	52	36·9	1010 C	·2191
Gorman Lake	94	53·9	53	04·7	963 B	·2419
Island Lake (HBC)	94	40·3	53	52·2	747 B	·3440
Island Lake (CNR)	94	40·7	53	52·2	751 B	·3436
God's Lake	94	27·9	54	33·3	618 C	·4084
Oxford House	95	16·0	54	57·0	639 C	·4401
Silsby Lake	95	42·1	55	28·1	639 C	·4576
Ilford (air)	95	41·6	56	03·6	610 B	·5555
Handle Lake	97	26·4	56	40·0	816 B	·5639
South Indian Lake	98	56·8	56	47·0	839 B	·5616
Northern Indian Lake	97	15·0	57	22·7	809 C	·6209
Southern Indian L. (north)	98	17·9	57	38·0	836 B	·6367
North Knife Lake (south)	97	06·1	57	57·2	904 C	·6622
North Knife Lake (north)	96	58·8	58	16·3	904 C	·6791
Farnsworth Lake	94	03·0	58	42·5	54 C	·7661
Berens River (air)	97	01·1	52	21·3	717 B	981·2099
Norway House	97	50·1	53	58·8	720 B	·3453
Moose Lake	100	18·1	53	42·4	839 B	·3406
The Pas (air)	101	11·9	53	49·1	858 C	·3360
Cormorant	100	36·0	54	13·8	843 B	·3527
Wabowden (air)	94	34·6	54	54·8	745 B	·4167
Thicket Portage (air)	97	41·8	55	19·3	597 B	·4883
Channing	101	49·9	54	44·7	963 B	981·3965
Pelican Narrows	102	56·0	55	10·1	1067 C	·4296
Island Falls	102	21·2	55	31·8	1001 B	·4598
Kamuchawie Lake	102	00·1	56	15·6	1160 B	·5154
South End	103	14·7	56	20·2	1148 C	·5143
Stanger Island	102	11·7	57	10·7	1153 C	·5897
Brochet (air)	101	40·0	57	52·7	1159 C	·6493
Wollaston Lake	103	26·9	58	05·8	1340 C	·6372
Waterfound Bay	104	01·1	58	48·7	1261 C	·7043

TABLE VI.—PRINCIPAL FACTS FOR GRAVIMETER BASES—*Concluded*

B. NORTHERN NETWORK—*Concluded*

Station Name	Longitude	Latitude	Elevation (Feet)	Observed Gravity
	° ′	° ′		
Black Lake	104 58·7	59 14·7	920 C	·7543
Stony Rapids (air)	105 51·1	59 15·9	696 B	·7902
Prince Albert (air)	105 41·0	53 12·7	1390 C	981·2299
Waskesiu	106 05·9	53 55·6	1750 C	·2709
La Ronge	105 17·8	55 05·9	1253 B	·3957
Stanley	104 33·2	54 25·0	1167 C	·4302
Ile-a-la-Crosse (air)	107 53·6	55 26·1	1385 B	·4069
Frobisher Lake	107 57·5	56 19·3	1384 B	·4740
Black Birch Lake	107 44·9	56 53·5	1582 C	·5121
Cree Lake (Waite)	106 50·8	57 20·3	1594 C	·5558
Mayson Lake	107 08·0	57 58·3	1414 C	·5990
Snare Lake	107 38·6	58 28·3	1442 C	·6504
Squirrel Lake	107 19·1	58 54·8	1210 C	·7135

The positions of the stations have been scaled from the largest scale maps of the National Topographic Series that are available for the area concerned. All bases of the southern network are located near bench marks, railway stations and the heights of these bases are known within one foot of elevation. The heights of stations in the northern network have accuracies designated in the table as A, B, or C, depending upon whether their uncertainties are within one foot, five feet or fifteen feet, respectively. Those classified as B heights have been determined by reference to tertiary levels along base lines and meridians, while the C heights have been determined barometrically.

The values of gravity have been derived solely from observations taken with the North American instrument, using the adopted scale constant value of 0·2315 milligals per scale division. It has been shown that the probable error of the gravity differences between bases is slightly less than 0·1 mgal. for the southern network and somewhat greater than this amount for the northern network. For the sake of uniformity the values of gravity for all stations have been rounded off to one-tenth of a milligal.

DESCRIPTION OF GRAVIMETER BASES

Diagrams illustrating the sites of twenty-four principal gravimeter bases in Ontario and twelve in the province of Quebec are given in the Appendix. Each diagram is oriented so that the approximate north direction is to the top of the drawing. The distances to the gravimeter bases from points of references, usually portions of buildings such as post offices, railroad depots, are shown in the diagrams. While these distances are exact, it should be mentioned that neither the configuration of the buildings nor their scale are necessarily precise.

Descriptions of the gravimeter bases of the northern network are not included in this report, but must await the installation of permanent bronze markers and the erection of monuments by which it is intended to mark the sites.

SUMMARY

A total of two hundred and seventy gravimeter bases were established during the 1952 field season as part of a general program to provide a framework for the control of existing and future gravity surveys. The observations form two separate networks, one in southern Ontario and Quebec and the other in Northern Canada.

The southern bases have been well connected and the standard deviation of the gravity differences estimated to be ± 0·08 mgals. The errors in the northern network, on the other hand, are about twice as large and may be related to the poorer performance of the instruments at that time. It is considered that the reliability of these results could be greatly improved by a few additional measurements to provide more closed loops within the existing networks.

The measurements made with the North American instrument, co-ordinated with the available pendulum station values, gave the calibration factor of the gravimeter to an accuracy of one part in a thousand. A comparison of the 1952 adopted values of gravity for identical bases observed with the same instrument on previous surveys suggests that the calibration factor of the North American gravimeter varies as much as 0·7 per cent per year.

The largest errors remaining in the adopted values of gravity for the base stations arise from the uncertainty of the calibration of the instruments and no improvement in the results can be expected until more precise pendulum determinations are obtainable. The gravimeter observations show that the majority of pendulum measurements have a standard deviation of about 1·2 milligals and that some of the observations made before 1936, and some in the unsettled regions of northern Canada have much larger errors.

Emphasis is now being given by the Dominion Observatory to the development of a modern pendulum apparatus, which it is hoped, will provide more consistent values of gravity and facilitate the extension of this gravimeter program to the now unsurveyed regions of Northern Canada.

ACKNOWLEDGMENTS

The authors are indebted to Mr. R. Bedford, graduate student at the University of British Columbia, for his assistance with the field observations, and to various staff members of the Dominion Observatory for their help in the reduction of the results.

REFERENCES

Cook, A. H.

1951 "An Investigation of the Errors of Some Recent Gravimeter Observations", *M.N.R.A.S., Geographical Supplement*, Vol. 6, No. 4.

Garland, G. D.

1950 "Interpretations of Gravimetric and Magnetic Anomalies on Traverses in the Canadian Shield in Northern Ontario", *Publications of the Dominion Observatory*, Vol. XVI, No. 1.

1953 "Gravity Measurements in the Maritime Provinces", *Publications of the Dominion Observatory* (in press).

Innes, M. J. S.

1953 "Gravity Measurements in Northern Ontario and Manitoba", *Publications of the Dominion Observatory* (in press).

McCollum, E. V. and Brown, A.

1943 "Use of the Gravity Meter in Establishment of Gravity Bench Marks", *Geophysics*, Vol. 8, No. 4.

Miller, A. H.

1931 "A Determination of the Relative Values of Gravity at Potsdam, Greenwich, Ottawa and Washington", *Publications of the Dominion Observatory*, Vol. XI, No. 2.

1936 "Gravity and Isostasy in Canada", *Publications of the Dominion Observatory*, Vol. XI, No. 3.

1944 "Gravimetric Surveys of 1944 in New Brunswick", *Geological Survey Bulletin*, No. 6.

1953 "Gravity Anomalies Over the Sudbury Basin", *Publications of the Dominion Observatory* (in press).

Nettleton, L. L.

1940 "Geophysical Prospecting for Oil", McGraw-Hill Book Co., p. 38.

Saxov, S.

1953 "Gravimeter Measurements in the Vicinity of Ottawa", *Publications of the Dominion Observatory* (in press).

Smith, A. E.

1951 "Graphic Adjustment by Least Squares", *Geophysics*, Vol. XVI, pp. 222–227.

Thompson, L. G. D. and Miller, A. H.

1953 "Gravity in Southern Ontario", (in press).

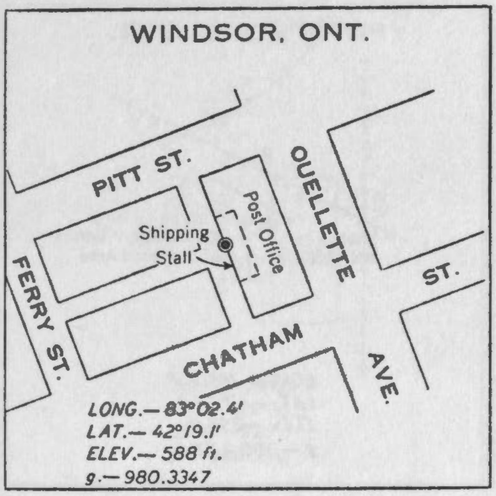
Worthing, A. G. and Geffner, J.

1948 "Treatment of Experimental Data", John Wiley & Sons, New York.

APPENDIX

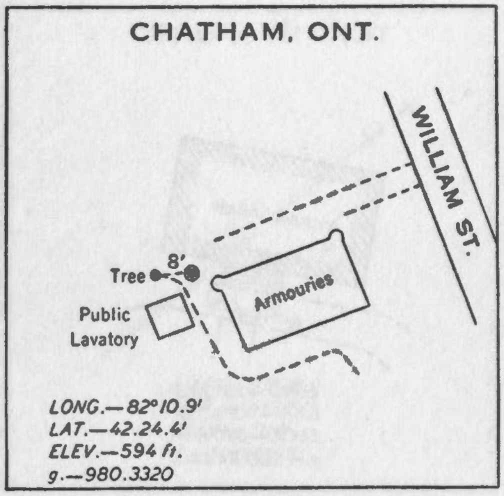
Descriptions of Sites of Gravimeter Bases

BASES IN ONTARIO



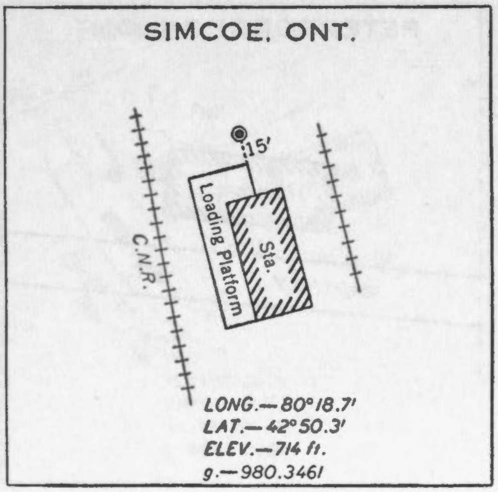
WINDSOR, ONT.

LONG.—83°02.4'
LAT.—42°19.1'
ELEV.—588 ft.
g.—980.3347



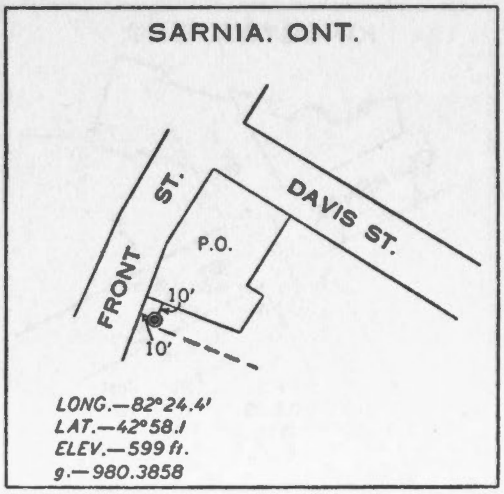
CHATHAM, ONT.

LONG.—82°10.9'
LAT.—42.24.4'
ELEV.—594 ft.
g.—980.3320



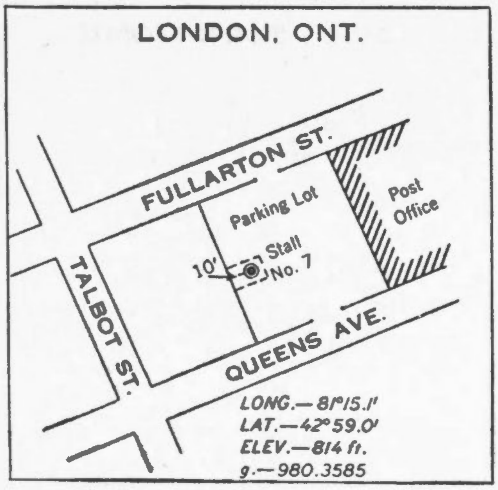
SIMCOE, ONT.

LONG.—80°18.7'
LAT.—42°50.3'
ELEV.—714 ft.
g.—980.3461



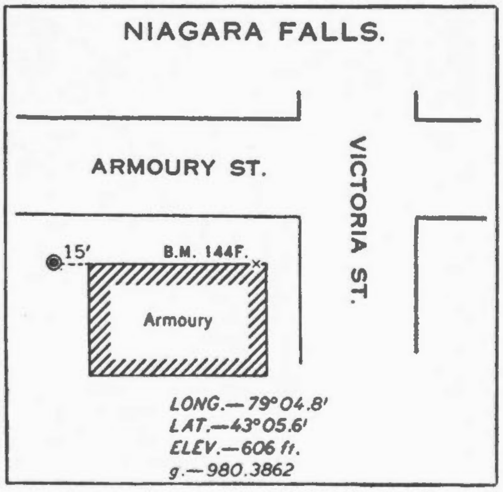
SARNIA, ONT.

LONG.—82°24.4'
LAT.—42°58.1
ELEV.—599 ft.
g.—980.3858



LONDON, ONT.

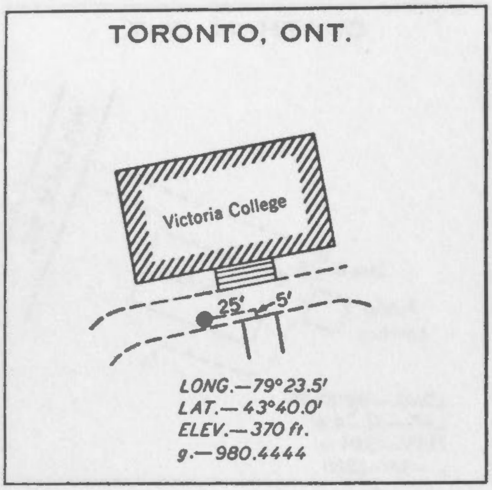
LONG.—81°15.1'
LAT.—42°59.0'
ELEV.—814 ft.
g.—980.3585



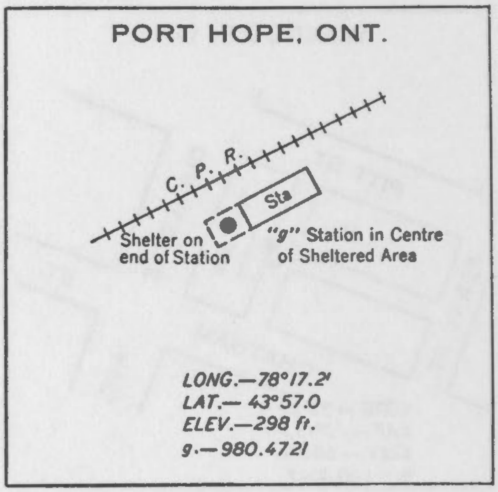
NIAGARA FALLS.

LONG.—79°04.8'
LAT.—43°05.6'
ELEV.—606 ft.
g.—980.3862

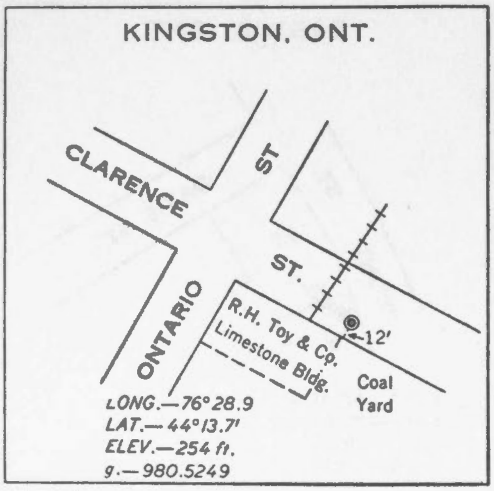
BASES IN ONTARIO


TORONTO, ONT.

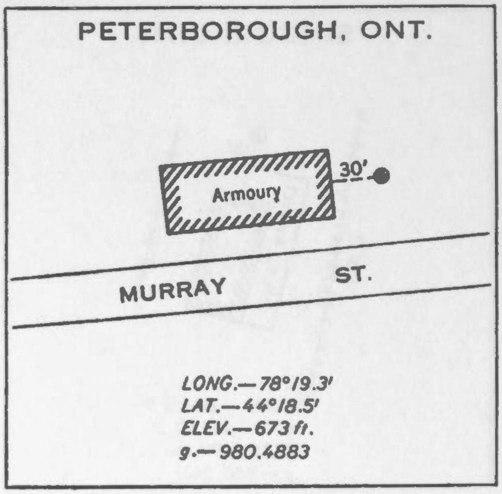
LONG.—79°23.5′
LAT.—43°40.0′
ELEV.—370 ft.
g.—980.4444


PORT HOPE, ONT.

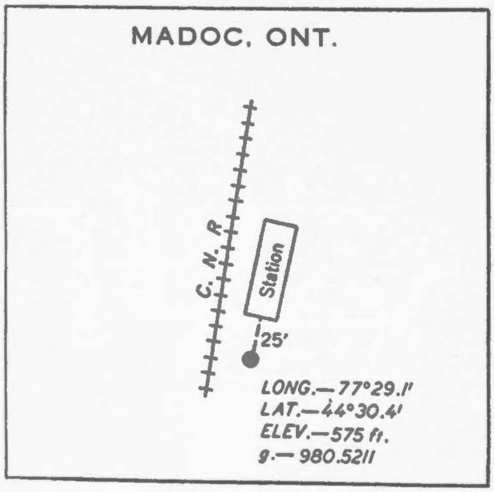
LONG.—78°17.2′
LAT.—43°57.0
ELEV.—298 ft.
g.—980.4721


KINGSTON, ONT.

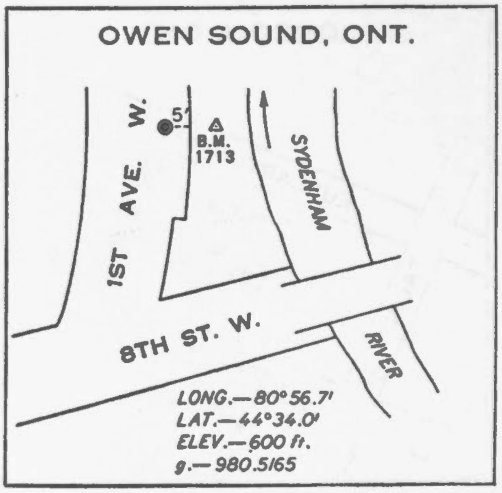
LONG.—76° 28.9
LAT.—44°13.7′
ELEV.—254 ft.
g.—980.5249


PETERBOROUGH, ONT.

LONG.—78°19.3′
LAT.—44°18.5′
ELEV.—673 ft.
g.—980.4883


MADOC, ONT.

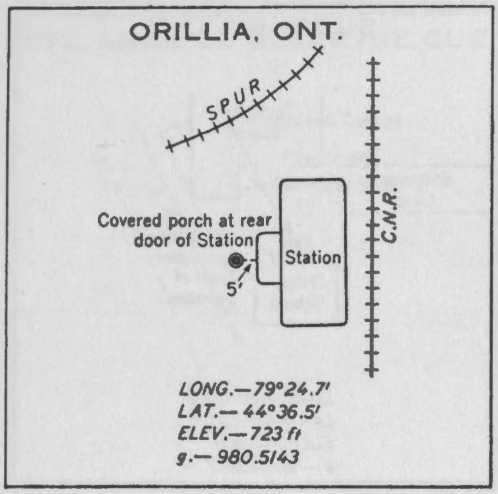
LONG.—77°29.1′
LAT.—44°30.4′
ELEV.—575 ft.
g.—980.5211


OWEN SOUND, ONT.

LONG.—80°56.7′
LAT.—44°34.0′
ELEV.—600 ft.
g.—980.5165

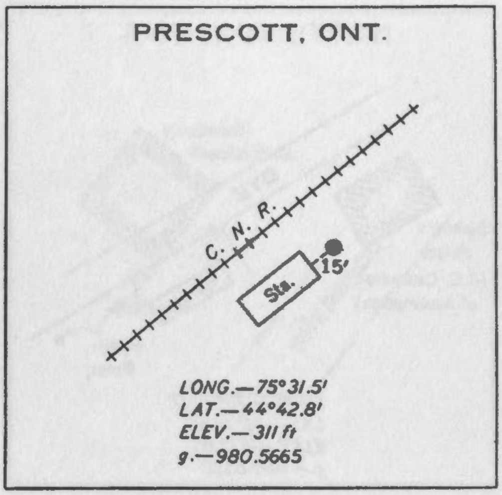
BASES IN ONTARIO

ORILLIA, ONT.



LONG.—79°24.7′
LAT.—44°36.5′
ELEV.—723 ft
g.—980.5143

PRESCOTT, ONT.

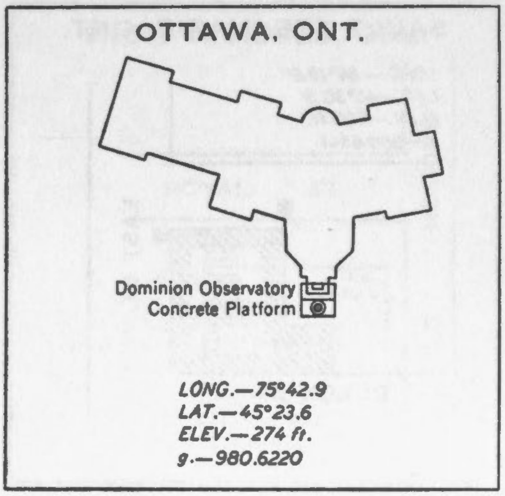


LONG.—75°31.5′
LAT.—44°42.8′
ELEV.—311 ft
g.—980.5665

HUNTSVILLE, ONT.

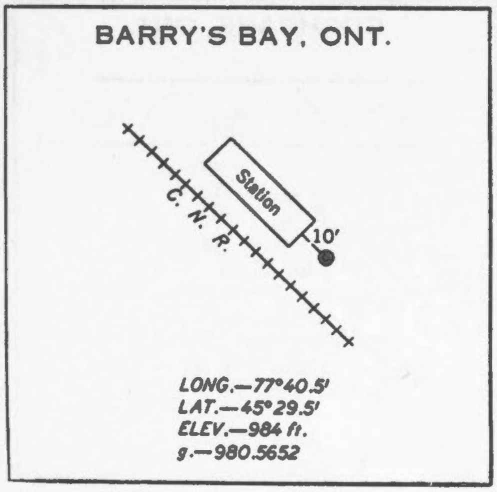
LONG.—79°12.9′
LAT.—45°19.3′
ELEV.—959 ft.
g.—980.5697

OTTAWA, ONT.



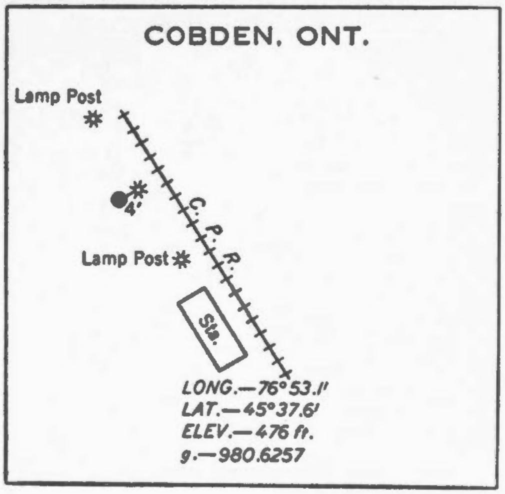
LONG.—75°42.9
LAT.—45°23.6
ELEV.—274 ft.
g.—980.6220

BARRY'S BAY, ONT.



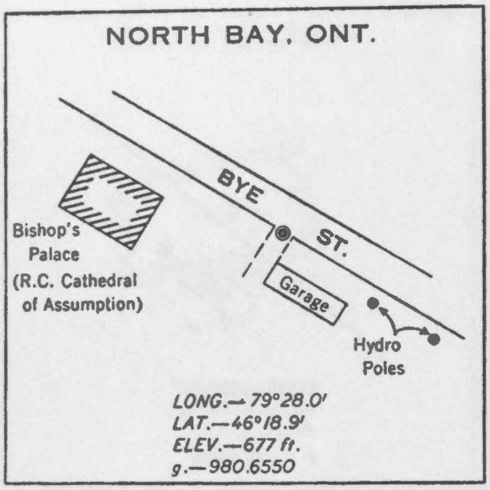
LONG.—77°40.5′
LAT.—45°29.5′
ELEV.—984 ft.
g.—980.5652

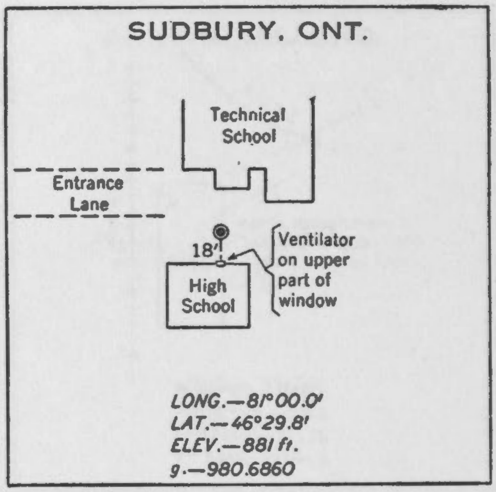
COBDEN, ONT.

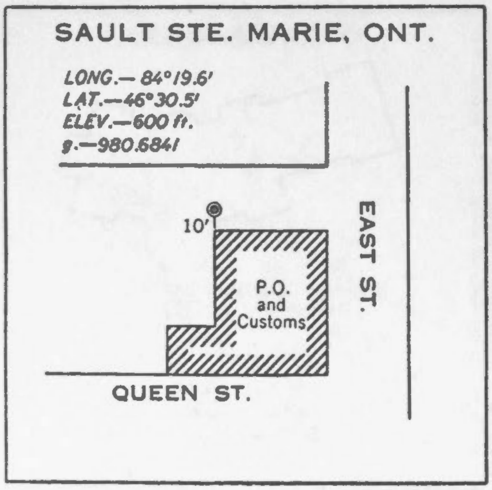


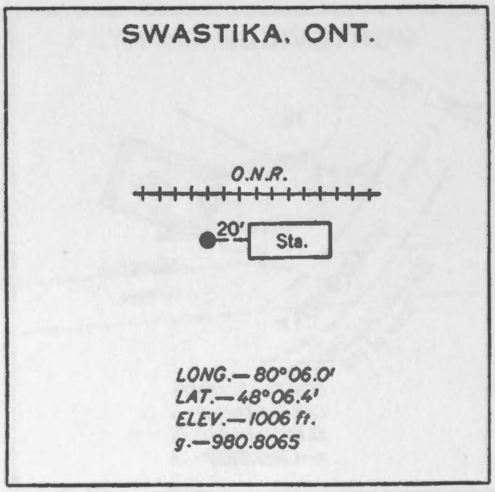
LONG.—76°53.1′
LAT.—45°37.6′
ELEV.—476 ft.
g.—980.6257

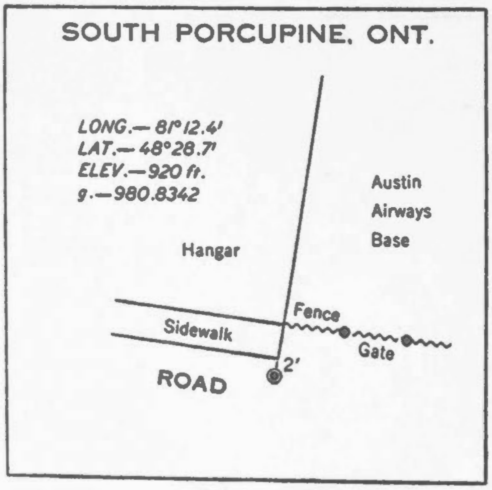
BASES IN ONTARIO

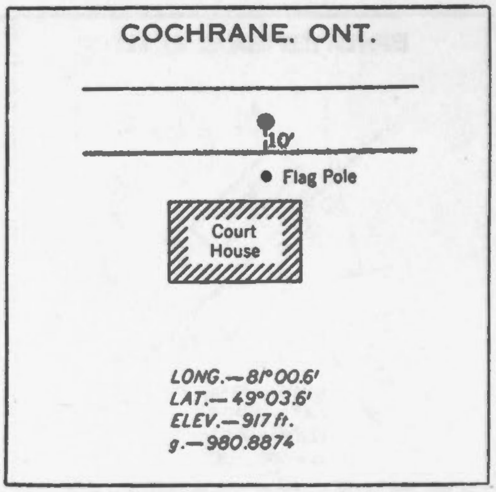




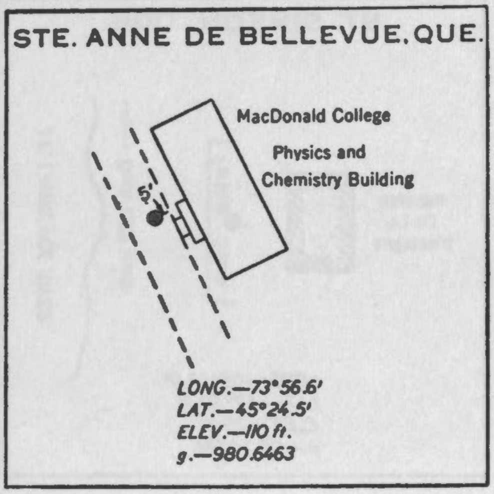




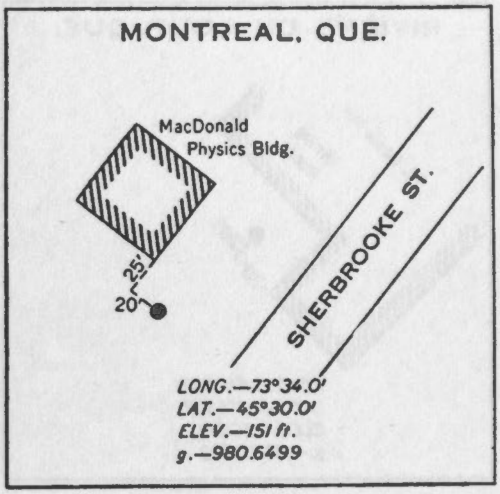




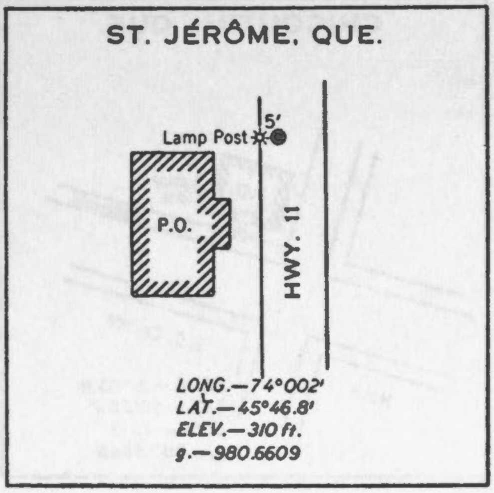
BASES IN QUEBEC



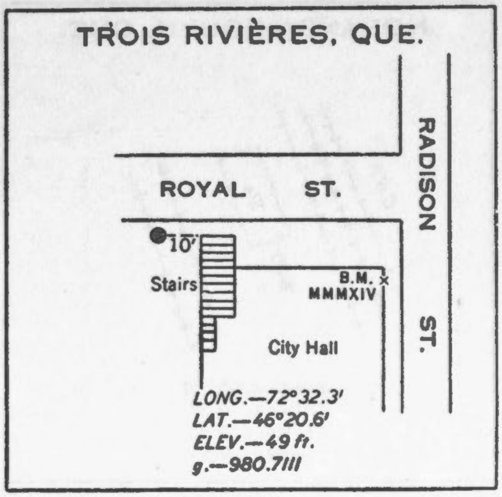
LONG.—73°56.6'
LAT.—45°24.5'
ELEV.—110 ft.
g.—980.6463



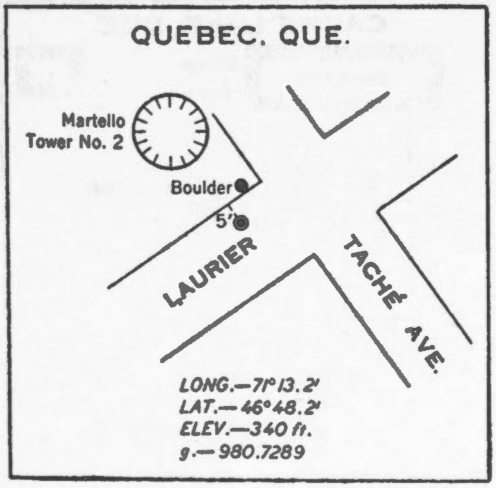
LONG.—73°34.0'
LAT.—45°30.0'
ELEV.—151 ft.
g.—980.6499



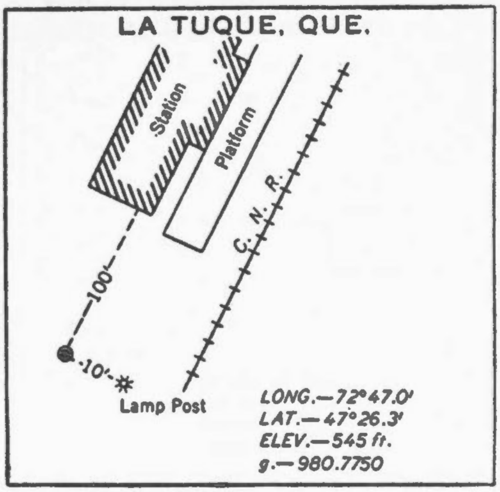
LONG.—74°002'
LAT.—45°46.8'
ELEV.—310 ft.
g.—980.6609



LONG.—72°32.3'
LAT.—46°20.6'
ELEV.—49 ft.
g.—980.7111

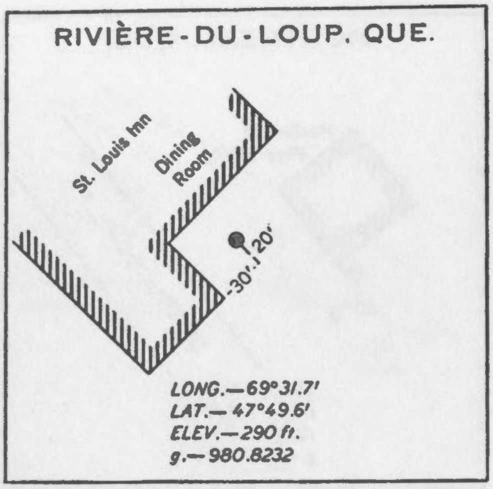


LONG.—71°13.2'
LAT.—46°48.2'
ELEV.—340 ft.
g.—980.7289



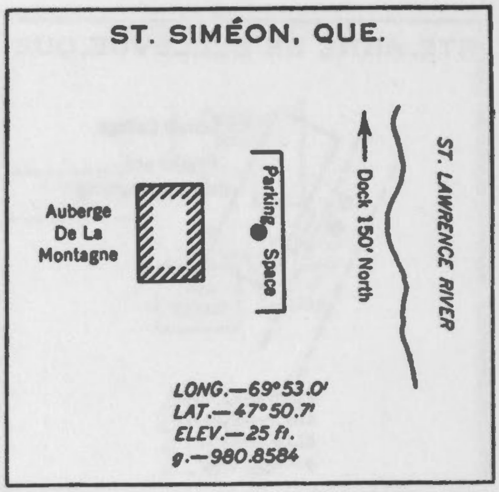
LONG.—72°47.0'
LAT.—47°26.3'
ELEV.—545 ft.
g.—980.7750

BASES IN QUEBEC



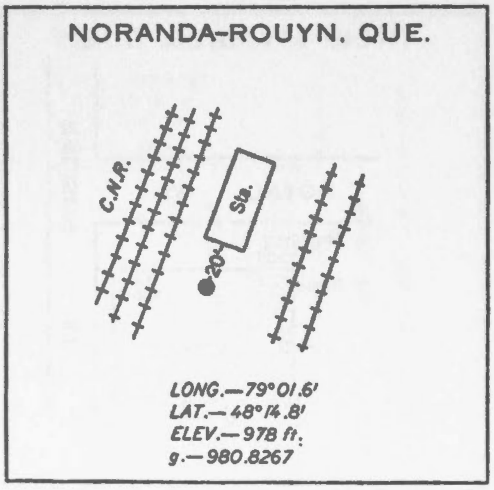
RIVIÈRE-DU-LOUP, QUE.

LONG.—69°31.7'
LAT.—47°49.6'
ELEV.—290 ft.
g.—980.8232



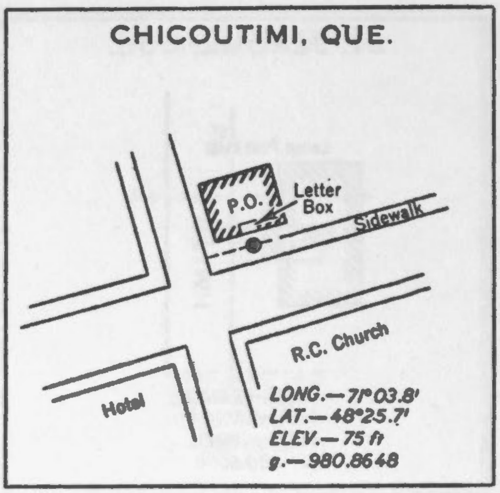
ST. SIMÉON, QUE.

LONG.—69°53.0'
LAT.—47°50.7'
ELEV.—25 ft.
g.—980.8584



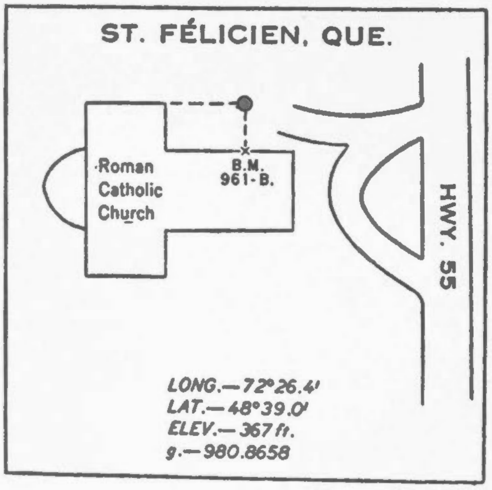
NORANDA-ROUYN, QUE.

LONG.—79°01.6'
LAT.—48°14.8'
ELEV.—978 ft.
g.—980.8267



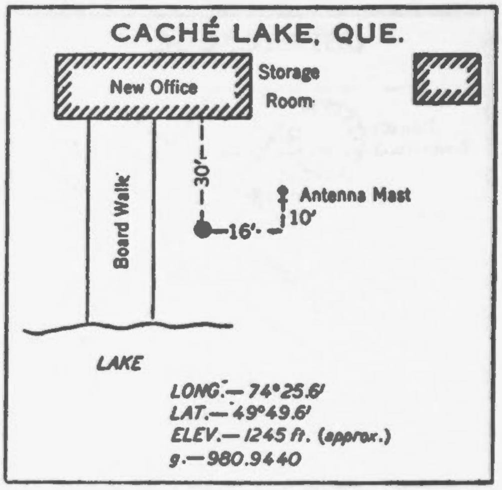
CHICOUTIMI, QUE.

LONG.—71°03.8'
LAT.—48°25.7'
ELEV.—75 ft
g.—980.8648



ST. FÉLICIEN, QUE.

LONG.—72°26.4'
LAT.—48°39.0'
ELEV.—367 ft.
g.—980.8658



CACHÉ LAKE, QUE.

LONG.—74°25.6'
LAT.—49°49.6'
ELEV.—1245 ft. (approx.)
g.—980.9440

CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
DOMINION OBSERVATORIES

PUBLICATIONS

OF THE

Dominion Observatory

OTTAWA

Vol. XVI, No. 9

Canadian West Coast Earthquakes, 195[illegible]

CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
DOMINION OBSERVATORIES

PUBLICATIONS

OF THE

Dominion Observatory

OTTAWA

Vol. XVI, No. 9

Canadian West Coast Earthquakes, 1952

BY

W. G. MILNE

EDMOND CLOUTIER, C.M.G., O.A., D.S.P., OTTAWA, 1953
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY

Canadian West Coast Earthquakes, 1952

BY

W. G. Milne

ABSTRACT

Local earthquakes recorded on the seismographs at Victoria, Alberni and Horseshoe Bay, British Columbia are tabulated, continuing a listing begun in 1951. Those twelve earthquakes which were felt are discussed separately. Epicentres are plotted on two maps, the first showing 1952 epicentres on a map of southern British Columbia, the second showing epicentres for both 1951 and 1952 shocks on a map of southern Vancouver Island. While it is yet too early to draw definite conclusions there appears to be a tendency for the epicentres to lie along definite lines, some of which coincide with known faults.

INTRODUCTION

An enlarged program for the study of West Coast earthquakes was begun in August, 1951. New stations were installed at Alberni and Horseshoe Bay. These stations, with the existing station at Victoria, provided the three station network necessary for the location of epicentres in the coastal regions of southern British Columbia. A paper[1] has already been published listing the epicentres determined during the latter part of 1951. The present paper continues this listing for the year 1952.

DESCRIPTION OF STATIONS

As during 1951 the Victoria station had as its equipment for the registering of local earthquakes a short-period vertical component Benioff seismometer. At Alberni the Willmore-Sharpe seismometers continued to operate for the whole year. No changes in the installation were made from 1951. At Horseshoe Bay the vertical and east-west components are of the Willmore-Sharpe design. A Sprengnether short-period horizontal seismograph ($T_g = T_s = 1{\cdot}9^s$) was substituted for the north-south component from February to October inclusive. At all other times the north-south too was a Wilmore-Sharpe. The recorders at all three stations operate at a paper speed of 60 mm/min.

The time control at Alberni and Horseshoe Bay was obtained from CBU Vancouver radio time signals, recorded on the instruments at 10 a.m. each day. During November and December the Alberni station recorded Mare Island (NPG San Francisco) and WWV (Washington) time signals whenever possible. At Victoria, CBU time signals were recorded until October, when a complete change was made to NPG signals at 3^h, 15^h, and 20^h GMT. If these signals continue to be satisfactory, a complete change-over of the network is contemplated to recording NPG signals for five minutes three times daily instead of CBU for twenty seconds once a day.

The station co-ordinates are listed below in Table 1.

METHOD OF LOCATING EPICENTRES

The method of locating epicentres has not been changed from the method used in 1951. That is, the differences of arrival times of the P waves at pairs of stations is used with the aid of a previously constructed map to obtain an approximate epicentre. This

---

[1] W. G. Milne and F. Lombardo, "Canadian West Coast Earthquakes, 1951", *Publications of the Dominion Observatory*, Vol. XVI, No. 3, 1952.

approximate epicentre and the origin time are adjusted to obtain the best fit for all three stations. The adjusted epicentre is then checked with the S-P times for each station. All of these earthquakes would appear to be from a very shallow depth. The few tremors near Victoria have an S-P time of the order of 3 seconds.

TABLE I

Station	Latitude			Longitude		
	°	′	″ N	°	′	″ W
Victoria	48	31	14	123	24	56
Alberni	49	16	14	124	49	18
Horseshoe Bay	49	22	39	123	16	33

Some indication of the possible error of location of an epicentre might be useful. To begin with let us assume the travel-time curves used are correct. The time error can amount to ±0·5 sec. for any one station. This would mean an error of approximately 3 km. for one direction. The epicentre would thus lie in a circle of 3 km. radius. In addition, the travel-time curves used were developed for use in the Canadian Shield where sedimentary rocks are not present. Their use in British Columbia, where there are considerable thicknesses of sedimentary rock, must lead to additional errors in location. Until crustal studies now under way in British Columbia have been completed it is impossible to estimate the effects of these sedimentary layers.

EPICENTRE LOCATION

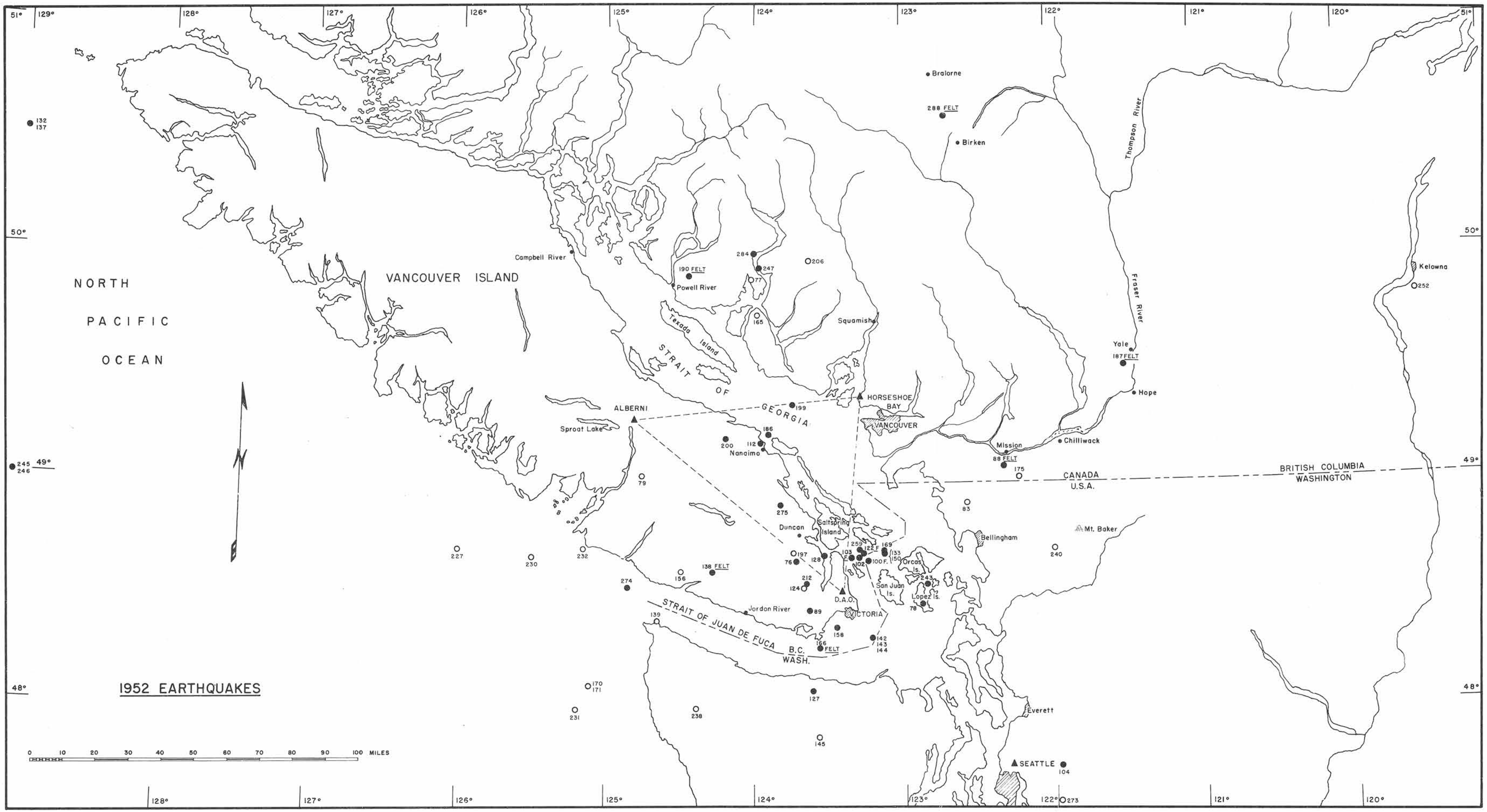
Table 2 lists the earthquakes recorded on the network stations during the year 1952. They are numbered consecutively with those of the earlier paper. All the epicentres for which satisfactory locations have been made are plotted on the attached map of southwestern British Columbia. Those epicentres which are considered to be accurately located are indicated by solid circles. For those shocks where a reading is obtained at only two stations some doubt usually exists as to which of two locations is the true epicentre. Such locations are marked on the map with open circles. Open circles are also used where an epicentre is so far from the triangle of stations that it cannot be well located. Epicentres from the United States Coast and Geodetic Survey epicentre program are included to make a total of 56 earthquakes plotted on the map.

DETAILS OF PARTICULAR EARTHQUAKES

Mission

An earthquake (No. 88) was felt in the general area of Mission and Abbotsford about 40 miles east of Vancouver on February 6th at 14:04 hours GMT. It was investigated in the field about four days after its occurrence to try to obtain an accurate epicentre. Table 3 shows the intensities felt in the area according to the Modified Mercalli Scale.

The area in question is heavily drift covered, and is bounded on the north, east, and south by mountains. Mission, Abbotsford, and Huntington and Sumas on the United States border all felt the earthquake with about the same intensity. For this reason no single point can be chosen for an epicentre, and the record data permit a wide range of



1952 EARTHQUAKES

TABLE 2—1952 EARTHQUAKES

No.	Date	Origin Time GMT	Lat. N.	Long. W.	Intensity	Arrival Times of P-Phase, GMT			Distance			Remarks
						Victoria	Horseshoe Bay	Alberni	V	HB	A	
			° ′	° ′						kms		
75	Jan. 2					22 52 28·4						
76	Jan. 4	2 14 10·0	48 39	123 44	II	2 14 16·4	2 14 26·4	2 14 29·5	27·1	88·1	105·6	Dilation to Victoria. Near Koksilah River.
77	Jan. 22	11 21 19·7	49 54	124 02	II	11 21 45·5	11 21 32·6	11 21 33·6	159	79	88	Powell River area.
78	Jan. 25	15 50 53·8	48 28	122 54	I	15 51 00·0	15 51 10·6	15 51 20·7	38·6	105	167	Lopez Island.
79	Jan. 25	17 43 06·3	49 02	124 45	II	17 43 25·0	17 43 25·5	17 43 11·2	114·5	117·0	28·5	South of Alberni.
80	Jan. 28				I	2 01 34·1	2 01 41·6					Probably in Washington State.
81	Jan. 29	23 45 45	43 30	127		23 47 11·0	23 47 24·8					U.S.C.G.S. epicentre.
82	Jan. 31							19 20 02·7				Near Alberni.
83	Jan. 31	22 43 12·3	48 54	122 36	II	22 43 23·8	22 43 23·7	22 43 39·6	72·1	72·0	166	In Washington State.
84	Feb. 1					1 23 46·1	1 24 02·5					
85	Feb. 1					17 08 05·5						
86	Feb. 5					0 48 20·1						
87	Feb. 6					12 04 57·5	12 05 09·7					South of Victoria.
88	Feb. 6	14 04 07·0	49 04·0	122 19·0	IV	14 04 23·6	14 04 19·9	14 04 35·7	101·4	78·0	186·1	Felt at Mission, B.C.
89	Feb. 6	20 25 39·1	48 26	123 38	II	20 25 42·1	20 25 56·9	20 26 00·1	17·5	101·8	127·6	West of Victoria.
90	Feb. 6		49 04	122 19	I	21 49 12·9	21 49 17·1					Probably aftershock of No. 88.
91	Feb. 7							0 35 37·8				Near Alberni.
92	Feb. 7		49 04	122 19	I	4 36 41·8	4 36 46·5					Probably aftershock of No. 88.
93	Feb. 7	22 03 46·8	49 04	122 19	I	22 03 03·3	22 03 00·1	22 03 16·1	101·0	80·8	185·5	South of No. 88. Felt at Sumas.
94	Feb. 9				I	5 29 08·5	5 29 09·6		86	96		West of Bellingham, Wash. (?).
95	Feb. 13							20 21 03·2				Near Alberni.
96	Feb. 14							17 13 54·0				Near Alberni.
97	Feb. 15					8 39 57·8		8 39 52·1				On west coast of Vancouver Island. (?)
98	Feb. 16					22 31 37·4		22 31 54·4				Possibly near No. 94.
99	Feb. 18							22 54 01·2				
100	Feb. 20	19 07 11	48 39	123 15	III	19 07 13·4	19 07 22·8	19 07 31·4	17	67	118	Felt in Victoria.
101	Feb. 21					7 53 15·1						
102	Feb. 21	23 35 47	48 40	123 18	II	23 35 51·5	23 36 00·9	23 36 09·1	19	80	130	Felt in Victoria. See notes.
103	Feb. 22	9 39 32·0	48 40	123 21	III	9 39 36·7	9 39 46·7	9 39 54·4	23	81	132	Felt in Victoria. See notes.
104	Feb. 23	9 06 42	47 45	121 58	II	9 07 05·2	9 07 16·6	9 07 24·4	140			These four minor tremors were felt near Duval in the state of Washington.
105	Feb. 23	9 17 04	47 45	121 58	I	9 17 27·4	9 17 36·0		140			
106	Feb. 23	9 28 02	47 45	121 58	II	9 28 25·5	9 28 36·8	9 28 45·1	140			
107	Feb. 23	9 54 29	47 45	121 58	II	9 54 52·3	9 55 06·5	9 55 14·4	140			

TABLE 2—1952 EARTHQUAKES—*Continued*

No.	Date	Origin Time GMT	Lat. N.	Long. W.	Intensity	Arrival Times of P-Phase, GMT			Distance			Remarks
						Victoria	Horseshoe Bay	Alberni	V	HB	A	
			° ′	° ′					kms			
108	Feb. 24						5 57 17					
109	Feb. 26					11 42 36	11 42 42·8	11 42 47·6				Teleseism.
110	Feb. 27						22 54 08·7					
111	Feb. 29				I	12 40 51·5	12 40 48·0					Probably near No. 88.
112	Mar. 2	0 11 53·6	49 10·0	123 58	III	0 12 07·4	0 12 02·9	0 12 04·0	84	57	63	Near Nanaimo.
113	Mar. 3							9 58 56·8			32	
114	Mar. 3							14 39 02·5			37	
115	Mar. 6							21 01 52·1				Probably a blast.
116	Mar. 7							20 39 00·6			87	
117	Mar. 7					20 53 52·9						
118	Mar. 8							15 30 35·4				Probably a blast.
119	Mar. 10							19 30 12·6				
120	Mar. 11							23 54 26·3				
121	Mar. 12							0 23 30·8				
122	Mar. 14	14 59 37·0	48 41	123 16	IV	14 59 42·6	14 59 51·5	15 00 00·1	33	70	140	Felt in Victoria.
123	Mar. 14							15 03 51·5				
124	Mar. 16	5 50 20·9	48 32	123 41	II	5 50 24·5	5 50 37·5	5 50 45·8	22	101	117	South Vancouver Island.
125	Mar. 16				II	17 20 30·4	17 20 43·5	17 20 53·5				Aftershock of No. 124. (?)
126	Mar. 20				I	10 11 42·2		10 11 58·6	31			Aftershock of No. 124. (?)
127	Mar. 20	21 36 18·5	48 05	123 37	II	21 36 27·2	21 36 42·9	21 36 43·9	54	149	158	Northern Olympic mountains.
128	Mar. 21	4 41 43·5	48 41	123 32	III	4 41 47·1	4 41 57·7	4 42 02·5	22	85	116	South Vancouver Island.
129	Mar. 22	2 01 35			III	2 01 58·7	2 02 08·9	2 02 15·9	142	215	292	South of Seattle.
130	Mar. 27					19 30 12·7			120			
131	April 1	00 37 41·5	48·0	113·8	VII	0 39 17·8	0 39 17·6	0 39 27·1				Felt in northwestern Montana and in British Columbia.
132	April 3	2 13 15	50·5	129	III	2 14 23	2 14 22·4	2 14 06·1				U.S.C.G.S.—off coast.
133	April 4	20 51 06·0	48 41	123 08	III	20 51 10·5	20 51 19·4	20 51 28·9	26	81	140	North of San Juan Island.
134	April 5					1 14 05·8			26			
135	April 8					3 56 45·9						
136	April 8				I			13 52 38·0			114	
137	April 8		50·5	129	II	15 28 39·0		15 28 21·4			146	Off coast of northern Vancouver Island.
138	April 11	9 48 37·5	48 36	124 17	IV	9 48 48·6	9 48 56·5	9 48 51·3	67	116	84	Felt in Victoria and south west Vancouver Island.
139	April 12		48 23	124 40	II	11 04 33·9	11 04 44·7	11 04 35·5				Possibly off Cape Flattery.

140	April 15					0 02 06·7						
141	April 16					17 56 18·1						Seattle 17:56:02.
142	April 16		48 19	123 13	III	22 25 41·1	22 25(12·2)*	22 25 58·8	27	118	158	Probably south east of Victoria.
143	April 16		48 19	123 13	II	23 31 15·6	23 31(33·2)*	23 31 35·0	27	118	158	Same as No. 142.
144	April 16		48 19	123 13	I	23 35 45·6		23 36 04·9	27		158	Same as No. 142.
145	April 17		47 53	123 35	II	00 27 45·6	00 27(37·6)*	00 28 02·2	76	155	178	Olympic mountain region.
146	April 17					18 57 39·3			83			
147	April 17					20 06 27·5						Very near Victoria.
148	April 17					22 45 03·8						Very near Victoria.
149	April 19					1 30 55·6						
150	April 19		48 41	123 08	II	19 05 54·5	19 05(21·0)*	19 06 12·4	26	80	139	Gulf Islands.
151	April 19					22 14 01·2						Very near Victoria.
152	April 20					0 07 13·5			38			
153	April 22					16 56 48·2			116			Seattle 16:57:00 (Δ=200).
154	April 24					11 04 36·9			75			
155	April 25		49 04	122 19	II	23 16 18·1	23 16 08·2	23 16 27·5	100			Possibly near No. 88.
156	April 27		48 36	124 30	II	5 27 32·8	N.O.†	5 27 32·2	83		82	Probably south west Vancouver Island.
157	May 1				II	13 09 07·6	13 09 20	13 09 23·1	211			Off Oregon coast.
158	May 1	20 12 36·8	48 21	123 28	III	20 12 40·7	20 12 56·1	20 13 00·1	24	117	141	Strait of Juna de Fuca, east.
159	May 3				I	00 10 00·6		00 10 05·6	44	64		
160	May 6							15 11 31·6				
161	May 7	16 14 36	51	131			16 15 50·2	16 15 36·2				Seattle 16:16:14. U.S.C.G.S. epicentre.
162	May 12				II	5 42 29·0	5 42 48·4	5 42 48·5	256	332		South of Victoria.
163	May 12					18 06 12·7						Very close to Victoria.
164	May 15							18 50 23·3				
165	May 17	7 36 07·5	49 44	123 59	II		7 36 18·1	7 36 20·8		67	79	Seechelt Peninsula area.
166	May 19	18 36 11·8	48 16	123 35	IV	18 36 16·7	18 36 32·3	18 36 35·2	30	125	142	Felt in Victoria. South west of city in Strait of Juan de Fuca.
167	May 30					23 31 12·2			191			
168	May 31					12 03 53·3			265			
169	June 2	8 59 34·0	48 42	123 08	II	8 59 38·8	8 59 46·6	8 59 56·4	28	76	138	Gulf Islands.
170	June 5		48·1	125·1	I	18 44 27·3		18 44 26·8	137			Probably off Washington coast.
171	June 5		48·1	125·1	I	19 05 55·6		19 05 55·2				Probably off Washington coast.
172	June 5				I	20 26 36·2			87			
173	June 5					21 14 50·2			147			
174	June 5		48·1	125·1	I	21 36 55·3		21 36 53·7				Probably off Washington coast.
175	June 5		49·01	122 13	I	23 52 28·7	23 52 26·8		105			Probably near No. 88, Mission, B.C.
176	June 6							15 00 31·9				

---

*Chronometer sticking, absolute time in doubt.

†Station not operating.

TABLE 2—1952 EARTHQUAKES—*Continued*

No.	Date	Origin Time GMT	Lat. N.	Long. W.	Intensity	Arrival Times of P-Phase, GMT			Distance			Remarks
						Victoria	Horseshoe Bay	Alberni	V	HB	A	
			° ′	° ′						kms		
177	June 7					16 51 41·7						
178	June 7					18 49 35						
179	June 12				I	13 28 59·6	13 29 13·2	13 29 32				Washington State. (?)
180	June 12				I	19 00 31·5	19 00 33·7					West of Bellingham. (?)
181	June 17				II	20 36 03·8	20 36 12·3	20 36 00·2	56	105		Entrance to Juan de Fuca Strait. (?)
182	June 18							5 11 45·2			66	
183	June 18							7 25 05·0			74	
184	June 18					10 58 57·0			106			
185	June 23				II	17 38 01·0	17 38 15·5	17 38 20·5				Probably south of Victoria.
186	June 23	23 52 42·6	49 12	123 54	III	23 52 56·5	23 52 51·3	23 52 53·2	85	51	66	North east of Nanaimo.
187	July 4		49 30	121 30	IV	22 54 57·6	22 54 50·4	22 55 07·1	148	119	256	Felt at Hope B.C. Seattle 22:55:09.
188	July 4				I		23 00 34·8			119		Aftershock of No. 187.
189	July 12				I	19 16 33·9	19 16 27·6	N.O.†		69		
190	July 15		49 54	124 27	III	10 08 36·8	10 08 29·8	N.O.†	180	93		Felt in Powell River.
191	July 16					18 59 03·7			69			
192	July 18							11 54 29·4				
193	July 18							11 55 21·1				
194	July 19		48·3	123·2	I	11 54 22·1			26			Felt in south east of Victoria, location approximately 11 kms. from city.
195	July 19		48·3	123·2	I	11 55 14·0			28			
196	July 23					6 50 11·1			62			
197	July 23		48 41	123 45	I	10 42 01·7		10 42 13·4	28		99	Lower Vancouver Island.
198	July 26					5 12 03·4					70	
199	July 26	14 13 51·5	49 20	123 45	III	14 14 07·1	14 13 58·1	14 14 03·4	96	37	76	East of Nanaimo.
200	July 26	21 03 11·1	49 11	124 12	II	21 03 26·7	21 03 23·2	21 03 18·3	95	73	44	West of Nanaimo.
201	July 27	19 52 14	47·5	122·4	IV	19 52 37·3	19 52 45·9	19 52 56·1	140	212	292	Seattle 19:52:24.
202	July 27	20 13 49	47·5	122·4	IV	20 14 12·8	20 14 21·0	20 14 31·5	140	212	292	Seattle 20:13:59. Seattle epicentre and origin time used.
203	July 28							8 25 04·2			103	
204	July 28					19 01 49·4			110			
205	July 29							23 50 31·0			76	
206	July 30		49 58	123 38	II		7 47 10·0	7 47 19·4		112	88	North east of Powell River, east of Jervis Inlet.
207	July 30				I		9 41 12·1	9 41 30				East of Vancouver, approximately 100 kms.
208	July 30							23 34 21·9			26	

209	Aug. 2		47·5	122·4		15 50 00·8	15 50 08·8					Seattle 15:49:43.
210	Aug. 6		47·5	122·4		17 32 17·6	17 32 31·6					Seattle 17:32:01.
211	Aug. 6							21 43 17·7			25	
212	Aug. 7	3 48 33·1	48 33	123 41	II	3 48 35·2	3 48 49·2	3 48 52·0	20	97	116	North west of Victoria.
213	Aug. 7						14 35 46·6					
214	Aug. 9						3 42 31·5					
215	Aug. 9						7 48 25	7 48 06·3				Off west coast of Vancouver Island.
216	Aug. 9							13 16 58·6			56	
217	Aug. 10							14 58 03·8			150	
218	Aug. 11					22 52 12·5			20			Felt in Victoria.
219	Aug. 11					22 59 31·3						Very near Victoria.
220	Aug. 11					23 01 09·1						Very near Victoria.
221	Aug. 18							6 39 23·0				
222	Aug. 19						3 07 08·9					
223	Aug. 20	15 24 59	43	127	IX	15 26 32·3	N.O.†	15 26 38·9				Off coast of Oregon. U.S.C.G.S. epicentre. M = 7-7½.
224	Aug. 21					5 00 58·2						Very near Victoria.
225	Aug. 21							12 53 56·2				
226	Aug. 21					19 09 56						Aftershock of No. 223.
227	Aug. 25		48·7	126·0		2 16 19	2 16 21·2	2 16 01·6				Off Barkley Sound, poor location.
228	Aug. 26					9 51 50·4			110			
229	Aug. 26						20 05 07·0					
230	Aug. 30		48 40	125·5	II	19 47 34·5		19 47 24·2			93	Off Barkley Sound.
231	Aug. 30		48·0	125·2	II	21 29 08·0		21 29 08·5	143			Off Washington coast.
232	Aug. 31		48 42	125 08		10 05 59·2	10 06 03·5	10 05 48·4	129	158	68	Off Barkley Sound.
233	Sept. 1					8 03 13·4						Seattle 8:03:08.
234	Sept. 2					3 51 20·0						Seattle 3:51:04.
235	Sept. 2					7 36 47						
236	Sept. 3					22 09 28·0						
237	Sept. 4							18 51 05·8				
238	Sept. 6		48·0	124·4			10 41 28·7	10 41 42·5				Olympic Peninsula.
239	Sept. 9							8 17 57·1				
240	Sept. 13		48·7	122·0		22 58 57·6	22 58 59·8	22 59 14·6	110	130	230	East of Bellingham.
241	Sept. 18							8 52 55·3				
242	Sept. 22							2 40 44·4				
243	Sept. 22	7 21 46·1	48 33	122 51	III	7 21 52·7	7 22 02·0	7 22 12·5	42	98	165	Near Lopez Island.
244	Sept. 30					0 54 18	0 54 33·2	0 54 36·6		200		South in Washington State.
245	Oct. 1	1 47 03	49	129	IV	1 48 01		1 47 51·2	410		340	Butte 1:49:55 U.S.C.G.S.
246	Oct. 1	1 53 33	49	129	V	1 54 31	1 54 33·5	1 54 20·7	410	440	340	Butte 1:56:21 epicentres.
247	Oct. 4	12 18 17	49 56	123 58	III	12 18 44	12 18 30·2	12 18 32·9	166	81	97	North of Seechelt Peninsula.
248	Oct. 4							12 47 15·0			80	

---

†Station not operating.

TABLE 2—1952 EARTHQUAKES—*Concluded*

No.	Date	Origin Time GMT	Lat. N.	Long. W.	Intensity	Arrival Times of P-Phase, GMT			Distance			Remarks
						Victoria	Horseshoe Bay	Alberni	V	HB	A	
			° ′	° ′						kms		
249	Oct. 7					14 20 39						
250	Oct. 9							9 24 36·1				
251	Oct. 11							9 03 45·1				
252	Oct. 11		49·8	119·5	IV	10 06 12	10 06 12·5					Felt at Kelowna, B.C.
253	Oct. 12		47·2	123·3		17 06 24·2	17 06 38·3	17 06 41·7	78	173	199	Seattle 17:06:10. Washington State.
254	Oct. 14					21 51 26·0	21 51 34·8					East of Victoria in Washington.
255	Oct. 18							14 00 48·5				
256	Oct. 19							12 21 11·6				
257	Oct. 20					3 20 31	3 20 01·7					
258	Oct. 21							15 36 36·8				
259	Oct. 21	21 10 33·2	48 42	123 17	III	21 10 37·3	21 10 45·7	21 10 54·2	23	76	129	Gulf Island area.
260	Oct. 28	15 55 27	48 42	123 18	III	15 55 31	15 55 39·5	15 55 47·7	23	76	128	Gulf Island area.
261	Oct. 29					3 42 58						
262	Oct. 29					4 39 31						
263	Oct. 29					6 57 56	6 58 09	6 57 57				Off coast.
264	Oct. 29					7 10 10						
265	Oct. 29					9 35 21	9 35 31	9 35 21				Off coast.
266	Oct. 29					20 04 06		20 04 07				Probably near Nos. 263 and 265.
267	Oct. 31					19 12 11·6	19 12 28·3	19 12 29·9				Not seismic.
268	Oct. 31					19 12 54·2	19 13 11·0	19 13 12·4				
269	Oct. 31					19 14 09·0	19 14 25·6	19 14 26·8				
270	Oct. 31					19 20 50·0	19 21 05·6	19 21 07·4				
271	Oct. 31					19 21 49·5	19 22 05·0	19 22 06·5				
272	Oct. 31					19 22 56·5	19 23 12·6	19 23 14·5				
273	Nov. 10		47·6	121·9	IV	22 54 30·7	22 54 40·4	22 54 48·8				Seattle 22:54:14. Felt near North Bend, Washington.
274	Nov. 19		48 32	124 49	III	12 28 03·2	12 28 10·4	12 28 00·9	97	165	81	Entrance to Juan de Fuca Strait.
275	Nov. 20		48 54	123 56	III	21 31 42·8	21 31 45·2	21 31 45·7	57	74	73	East of Lake Cowichan.
276	Nov. 21					19 53 34·7	19 53 15·7					
277	Nov. 21					21 34 29·2	21 34 44·1	21 34 46·6				Not seismic.
278	Nov. 21					21 35 56·2	21 36 10·6	21 36 13·1				
279	Nov. 21					21 36 31·8	21 36 45·9	21 36 48·6				
280	Nov. 21					21 37 20·5	21 37 35·1	21 37 37·6				
281	Nov. 21					21 37 35·1						

282	Nov. 23	...	...	...	...	0 16 50·7	...	00 16 51·1	...	
283	Nov. 24	...	...	...	I	23 17 46	23 17 24	23 17 38	...	Readings doubtful.
284	Nov. 26	...	50·0	124·0	II	6 30 21·2	6 31 03·3	6 31 09·1	...	Jervis Inlet.
285	Dec. 8	...	...	...	...	16 41 17·8	...	...	...	
286	Dec. 9	...	...	...	...	...	...	9 20 28·7	...	
287	Dec. 9	...	...	...	...	19 37 59·5	19 38 12·0	19 38 07·5	...	Not earthquake.
288	Dec. 10	...	50·6	122·7	IV	13 55 19·0	13 55 07·8	13 55 16·2	281 145 212	Felt at Pioneer Mine, B.C.
289	Dec. 10	...	...	...	...	17 07 42·0	17 07 58·3	17 08 02·6	...	Not earthquake.
290	Dec. 12	...	...	...	...	...	...	17 36 13·1	...	
291	Dec. 16	...	...	...	...	5 43 40·9	...	...	...	
292	Dec. 26	...	...	...	...	21 35 47·6	21 35 56·9	...	...	South of Victoria.

choices along the line of the valley since the epicentre lay to the east of all the stations. The felt region extends about one mile east and one mile west of the valley.

At Mission some woodpiles were reported to have been toppled, but on the field survey none could be found. No other damage was reported. Throughout the area it was reported that a noise like a rumbling truck accompanied the earthquake, and in Mission itself (rock at this point) one person thought a truck had struck the house. People were awakened by this noise along the valley. The noise and the tremor were not noticed north of Mission beyond the first plateau.

At Sumas an aftershock was reported on the following afternoon by one person, and this coincided with a small trace on the Horseshoe Bay record at 22:44 on February 7th.

TABLE 3

Intensity III

Mission, Matsqui, Abbotsford, Huntington, Sumas.

Intensity II

Hatzig, Hatzig Lake.

Not Felt

Haney, Steelhead, Ruskin.

Victoria

During 1952 several earthquakes were felt in the vicinity of Victoria. Contrary to some reports, none of these earthquakes did any damage.

There were three tremors in as many days on the 20th, 21st, and 22nd of February. The first (No. 100) was felt in Victoria and Sidney, B.C., at 19:07 GMT. The intensity was scarcely more than II on the scale. It was felt at the Observatory as the rumble of a truck. The smaller tremor (No. 102) on the next afternoon at 23:36 was felt generally, and again at the Observatory. At 9:39 on February 22nd many people in Victoria were awakened by the third and strongest tremor of this series (No. 103). It was felt at Sidney, Saltspring Island, San Juan Island, but not at Duncan, Nanaimo, or Vancouver. This earthquake and the next at 14:59 GMT on March 14th (No. 122) were felt in Alberni, and in fact alarmed many residents. That of March 14th was felt in Victoria as well as Jordan River, Port Angeles, Vancouver, and Saltspring Island but not Duncan or Nanaimo. These four tremors were located instrumentally under Haro Strait between Sidney and the International Border.

Tremors on April 11th at 9:49 (No. 138) and on May 19th at 18:36 (No. 166) were located on south-west Vancouver Island and south of Victoria in the Strait of Juan de Fuca respectively. Apparently in both cases the area around Jordan River felt the tremors more strongly than in the previous earthquakes for there was a request for information on the epicentre from the British Columbia Electric Company's office in order that they might decide on the wisdom of patrolling their power lines in that region. Although farther from Vancouver than the four previous shocks, the tremors were well pronounced in various parts of that city.

After the California earthquake in July, the Victoria local newspapers published a paragraph to the effect that the seismologist at the Observatory would welcome any reports on local tremors. In a few days there were many telephone enquiries about rumblings that various residents thought were earthquakes. To date only one of these reports has led to the discovery of an earthquake, a very weak tremor on the Victoria records. That is No. 218 at 22:52 hours on August 11th. The tremor apparently was located just off the south end of the city. Similar disturbances (Nos. 194 and 195) were felt in Victoria on July 19th. Again the epicentre must be very close to the south-east coast of the island for the felt region is limited to a few streets.

South-East British Columbia

An earthquake (No. 131) whose epicentre has been placed by the United States Coast and Geodetic Survey on the east side of Flathead Lake in northwestern Montana, was felt in Canada. Questionnaires sent out after the tremor yielded the knowledge that the earthquake was felt at Fernie and Newgate in British Columbia. For this reason the earthquake is listed in the 1952 earthquakes. It occurred on April 1st at 00:38 hours GMT. Maximum intensity at the epicentre is given as VII on the Modified Mercalli Scale.

Hope

Along the Fraser River Canyon in the region of Hope and Yale a sharp tremor (No. 187) was felt at 22:55 hours on July 4th. The list of centres where this earthquake was felt is given in Table 4. Province of British Columbia highway construction crews felt the tremor between Hope and Spuzzum and noticed some boulders set into motion by the vibrations. A flour sack was reported overturned at Hope.

It appears that the earthquake was not felt east of the Fraser River, nor south of Hope. The instrumental epicentre is in the mountain region west of Yale, so the two facts put together seem to fix the epicentre between Harrison Lake and the Fraser River. There is one isolated centre, Abbotsford, where two people felt the tremor whereas communities closer to the epicentre felt nothing. This would seem to indicate that the Mission tremor was actually at the north end of the valley near Mission, and Abbotsford, reporting a strong intensity, did so because of local conditions.

A second tremor six minutes later was felt generally around Hope, Yale, and Spuzzum.

TABLE 4

Place	Intensity	Place	Intensity
Yale	IV	Chilliwack	0
Hope	IV	Princeton	0
Spuzzum	III	Abbotsford	II
North Bend	III	Mission	0
Lytton	0	Agassiz	0

Powell River

An earthquake (No. 190) was reported by a few persons at Powell River on July 15th at 10:09 hours GMT. No other centre appears to have felt the tremor, although a good record was obtained on the seismograms.

Kelowna

Questionnaire forms, distributed in the area after an earthquake reported from Kelowna on October 11th (No. 252) show that two isolated centres felt the tremor quite strongly. However, places between or near Kelowna and Grand Forks reported no disturbance at all. It is quite possible that the epicentre was nearer Kelowna for the Horseshoe Bay and Victoria records indicated that source. The intensity rating for either of these centres was less than III. Alberni did not record the earthquake.

Pioneer Mine

A tremor (No. 288) which registered slightly at Butte, Montana, awakened persons in Pioneer Mine and Birken, B.C. at 13:55 GMT, December 10. No damage has been reported. Records were strong at all three stations in the network. The felt area would appear to be elliptical in shape with the major axis in a north-west direction, as neither Pemberton nor Seton Lake reported a tremor.

DISCUSSION OF EPICENTRES

While it is still too early to draw any final conclusions from the location of epicentres, it is interesting to combine the data obtained to date on a single map. This has been done for the southern part of Vancouver Island on the map of Figure 2. The map also shows the location of some known faults. These have been taken from a paper by Clapp.[2]

Examination of the figure seems to give some indications of correlation between epicentres 15, 274, 156, 138 and 64 and a known fault. A second well-defined line seems to pass northwestward from epicentres 166 to 197; it might possibly be extended still farther north through epicentres 275 and 200. These patterns may of course have no significance whatever, but they at least suggest that regularities in the arrangement of epicentres may eventually emerge.

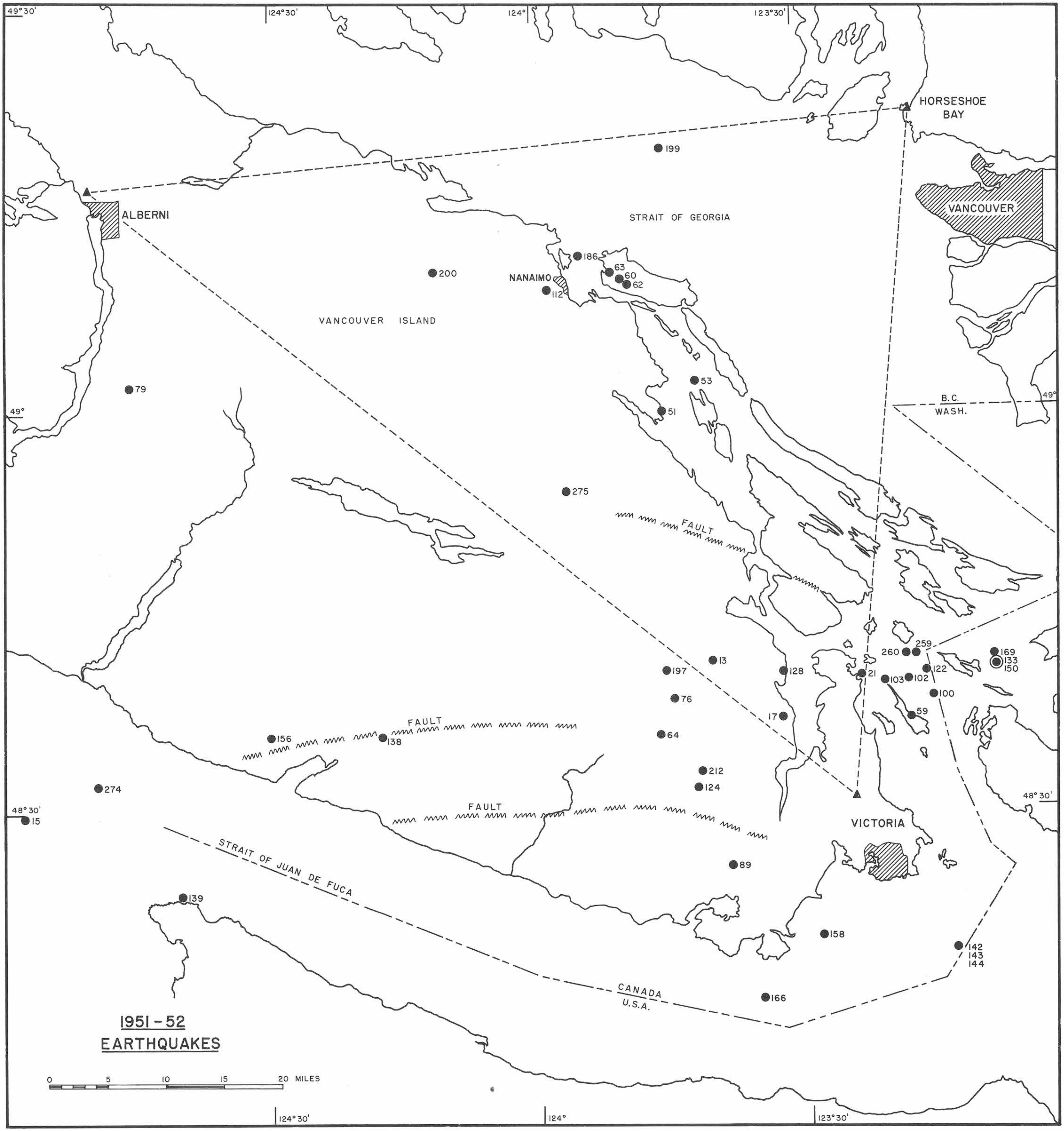
An outstanding feature about epicentres in the southern part of the island is that they are usually felt strongly in Alberni, although Duncan and Nanaimo, which are frequently closer to the epicentres, report no notice of the earthquakes. Residents of Alberni continue to be disturbed by each event. Alberni is in a valley almost totally surrounded by sedimentary rocks forming mountains. In the valley itself are one or more outcropings of volcanic rocks. During the 1946 earthquake considerable damage was reported from Alberni although the epicentre was on the other coast of the island.

The epicentres at Mission, at Hope, at Kelowna, and at Pioneer Mine appear to be isolated events to date. Perhaps such can be expected in the mountainous interior of British Columbia. It would not be surprising if there were minor tremors in that area of British Columbia along the continental divide north of Montana. The Montana seismologists report epicentres up to the border, and it seems reasonable to expect that similar disturbances would be detected farther north. In fact, although no record was obtained, it seems certain that the Banff area was shaken by a tremor on March 3rd.

Again as in the past there were several tremors, apparently along the continental shelf as far west as 129°. These are well recorded on the instruments but because more

---

[2] Charles H. Clapp, "Geology of the Victoria and Saanich Map Areas, Vancouver Island, B.C.", *Geological Survey of Canada*, Memoir No. 36, 1913.



1951 - 52 EARTHQUAKES

westerly control is lacking the epicentres are approximate only. Along the west coast of Vancouver Island several small tremors have been located, but not in sufficient number to indicate any trend in direction. A few scattered earthquakes (very small) were centred south of Alberni.

Around Nanaimo, both west of the city on the island and east in the Gulf of Georgia, there are several good locations. These earthquakes are not reported as felt by anyone in the area, although some are quite sharp. Towards Powell River there are more epicentres than in 1951, one of them (July 15) having been felt.

The instruments record from time to time earthquakes in Washington State, but no precise location is given on the map. Arrival times are listed in Table 2 for reference by other seismologists. One tremor in the Queen Charlotte Islands area was well recorded at all stations although the distance involved is greater than the range in which the Willmore-Sharpe instruments were expected to operate.

During 1952 seismological reports have been received from Butte, Montana, and from Seattle, Wash. In some cases the readings from these stations have been used to determine epicentres. Such an exchange of information can be very beneficial to all stations concerned.

Dominion Astrophysical Observatory,
Victoria, B.C.
August 20, 1953.

CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
DOMINION OBSERVATORIES

PUBLICATIONS

OF THE

Dominion Observatory

OTTAWA

Vol. XVI No. 10

TABLES OF EXTENDED DISTANCES FOR PKP AND PcP

BY

J. H. HODGSON AND J. F. J. ALLEN

EDMOND CLOUTIER, C.M.G., O.A., D.S.P.
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
OTTAWA, 1954

Tables of Extended Distances for PKP and PcP

BY

J. H. HODGSON AND J. F. J. ALLEN

ABSTRACT

Tables of extended distances for PKP_1, PKP_2 and PcP are presented, for surface focus and for focal depths ranging from 0·00R to 0·12R by steps of 0·01R. The tables are based on the Jeffreys-Bullen travel-time curves for the equivalent phases. They are consistent with earlier tables giving extended distances for P, so that the several phases can be used in a single solution.

INTRODUCTION

This is the third paper of a series dealing with theoretical aspects of Byerly's method of determining the direction of faulting in an earthquake. The first paper[1] reviewed the method as it applies to earthquakes of normal focus, and provided some criteria for testing the geometrical validity of solutions. The second paper[2] gave tables of extended distances for P waves originating at various focal depths, thereby permitting application of the method to deep focus earthquakes. Since these tables do not permit use of data for stations beyond the range of P, a need was felt for tables of extended distances for the phases PKP_1 and PKP_2, refracted through the core. In preparing these tables it has been possible, with little additional effort, to provide tables also for PcP, the phase reflected from the core.

THE PHASES PKP_1 AND PKP_2

In order that there may be no misunderstanding about the phase designation used in this paper, a discussion of the Jeffreys-Bullen[3] PKP curve will first be given. The curve is shown in Figure 1. It consists of three segments, AB, BC, and DF, and there are theoretical reasons for believing that a fourth segment, connecting C to D must exist. If we admit this segment then the curve may be conveniently regarded as a single curve with cusps.

An insert to Figure 1 defines the angle e which a ray makes with the tangent to the surface. The discussion of PKP will be in terms of this angle e. For a surface focus, e is defined by the equation

$$\cos e = v \frac{dt}{d\Delta},$$

where v is the velocity of seismic waves at the surface and $dt/d\Delta$ is the inverse slope of the travel-time curve at the point where the ray emerges. By determining the value of $dt/d\Delta$ at any point on a curve, one can compute the angle at which the ray, reaching that point,

---

[1] J. H. Hodgson and W. G. Milne, "Direction of Faulting in Certain Earthquakes of the North Pacific," *Bull. Seism. Soc. Am.* Vol. 41, 221–242, 1951.

[2] J. H. Hodgson and R. S. Storey, "Tables Extending Byerly's Fault-Plane Techniques to Earthquakes of any Focal Depth," *Bull. Seism. Soc. Am.*, Vol. 43, 49–61, 1953.

[3] H. Jeffreys and K. E. Bullen, *Seismological Tables*, (Brit. Assoc. Adv. Sci., 1940.)

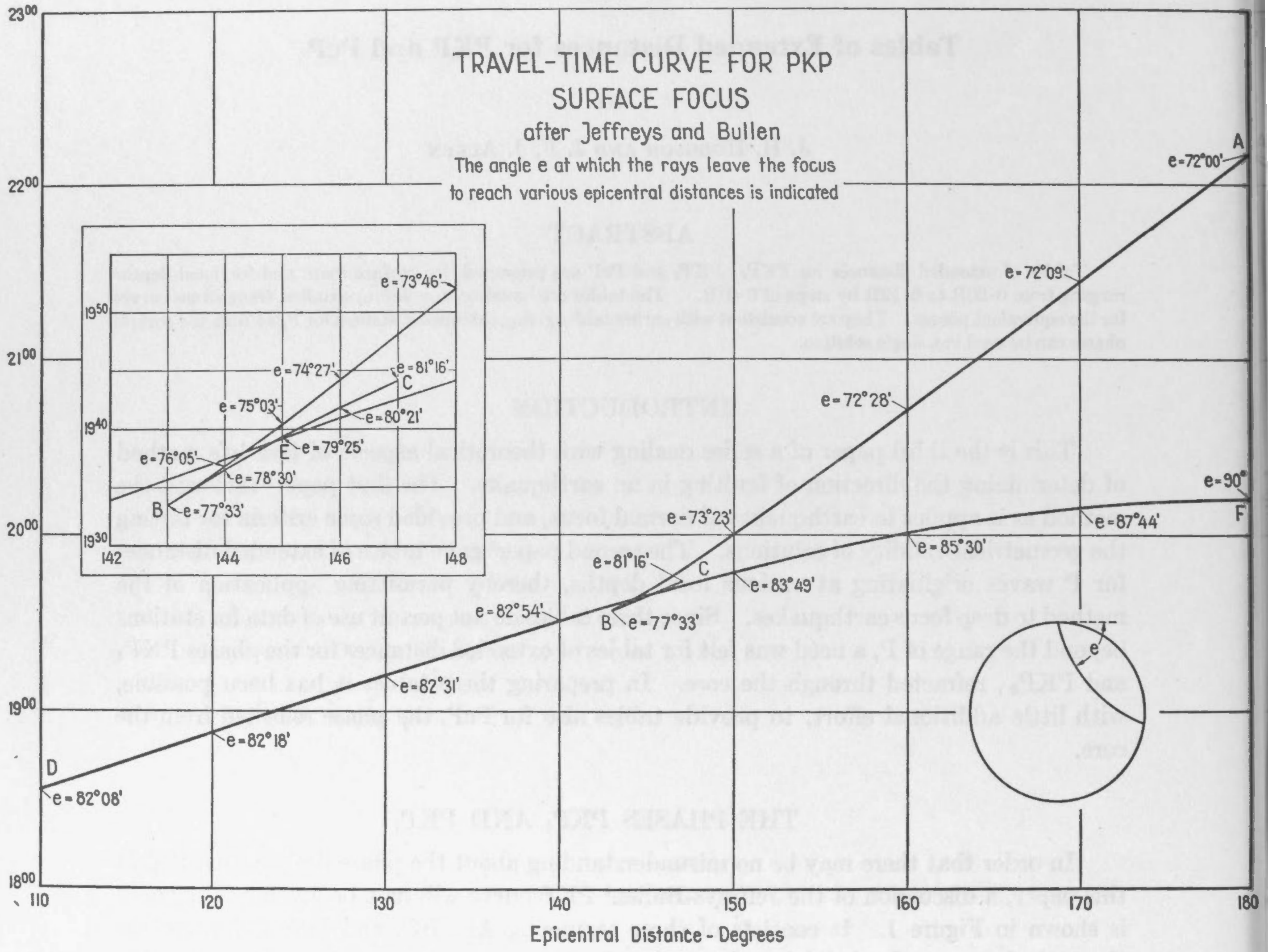


FIGURE 1

left the focus. For example, when this analysis is applied to the surface-focus P curve of the Jeffreys-Bullen tables it is found that the angle *e* varies from 0° to about 72° as the ray sweeps out to 105° epicentral distance.

When a similar analysis is applied to the core phases of Figure 1 it is found that the point A corresponds again to a value of *e* of about 72°; for a very slight increment in the angle *e* the point of emergence jumps from a P at 105° to a PKP at 180°. As one moves down the upper branch of the curve from A the slope varies continuously until the point B is reached. The value of *e* corresponding to the point B is 77° 33′. Thus, while *e* grows from 72° to 77° 33′, the ray sweeps from 180° epicentral distance back to 143°.

Next consider the section of the curve BC. BC and AB come together tangentially at B so that there is no discontinuity in slope as we switch from one branch of the curve to the other. As the curve BC is traversed from B to C, the angle *e* varies from 77° 33′ to about 81° 16′, while the point of emergence varies from 143° to 147° epicentral distance.

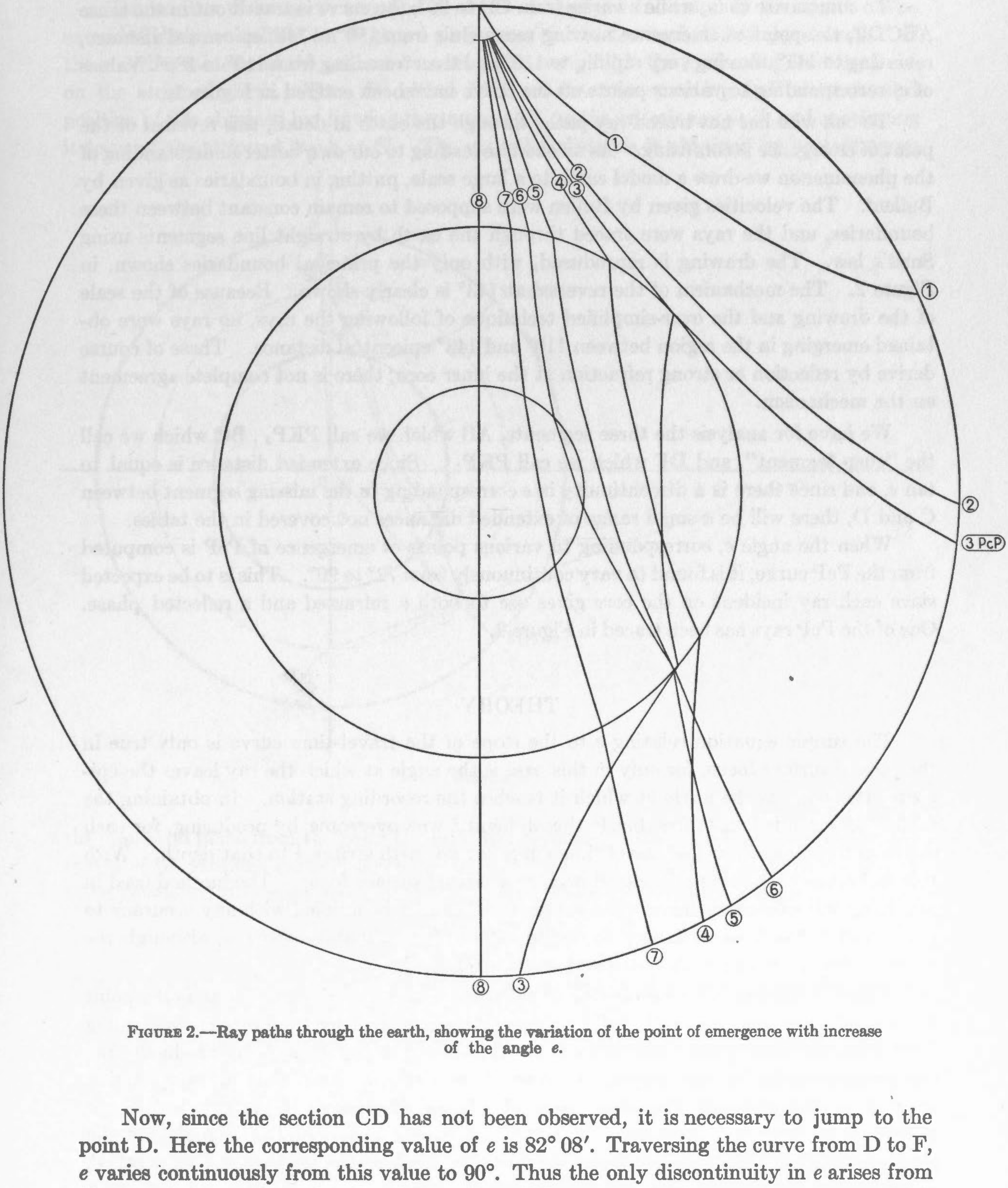


FIGURE 2.—Ray paths through the earth, showing the variation of the point of emergence with increase of the angle *e*.

Now, since the section CD has not been observed, it is necessary to jump to the point D. Here the corresponding value of *e* is 82° 08′. Traversing the curve from D to F, *e* varies continuously from this value to 90°. Thus the only discontinuity in *e* arises from the jump between the points C and D, and would be covered by the missing segment which must join BC tangentially at C and DF tangentially at D.

To summarize then, while e varies from 72° to 90°, the curve is traced out in the sense ABCDF, the point of emergence moving meanwhile from 180° to 143° epicentral distance, reversing to 147°, moving very rapidly to 110° and then travelling from 110° to 180°. Values of e, corresponding to various points on the curve have been entered in Figure 1.

To one who has not traced ray paths through the earth in detail, this reversal of the point of emergence is confusing. As an exercise leading to our own better understanding of the phenomenon we drew a model earth to a large scale, putting in boundaries as given by Bullen[4]. The velocities given by Bullen were supposed to remain constant between these boundaries, and the rays were traced through the earth by straight line segments using Snell's law. The drawing is reproduced, with only the principal boundaries shown, in Figure 2. The mechanism of the reversal at 143° is clearly shown. Because of the scale of the drawing and the over-simplified technique of following the rays, no rays were obtained emerging in the region between 110° and 143° epicentral distance. These of course derive by reflection or strong refraction at the inner core; there is not complete agreement on the mechanism.

We have for analysis the three segments, AB which we call PKP_2, BC which we call the "cusp segment", and DF which we call PKP_1. Since extended distance is equal to tan e, and since there is a discontinuity in e corresponding to the missing segment between C and D, there will be a small range of extended distances not covered in the tables.

When the angle e, corresponding to various points of emergence of PcP is computed from the PcP curve, it is found to vary continuously from 72° to 90°. This is to be expected since each ray incident on the core gives use to both a refracted and a reflected phase. One of the PcP rays has been traced in Figure 2.

THEORY

The simple equation relating e to the slope of the travel-time curve is only true in the case of surface focus, for only in this case is the angle at which the ray leaves the epicentre the same as the angle at which it reaches the recording station. In obtaining the tables[2] of extended distances for P this difficulty was overcome by producing, for each depth of focus considered, a travel-time curve for an earth stripped to that depth. With this technique each focus considered became a virtual surface focus. The method used in obtaining stripped-earth travel-time curves for P cannot be applied with any accuracy to PKP, and it has been necessary to devise a more fundamental approach, although the general idea of dealing with a stripped earth is retained.

Figure 3 represents a cross-section of the earth with an earthquake focus at the point F, at depth d within the earth. A ray, generating a typical PKP and its corresponding PcP, is shown leaving the focus at an angle e_d, defined in the figure. By producing the ray symmetrically to the surface a point A is defined, such that a ray starting from A would generate the same pair of phases illustrated. This ray leaves the surface at an angle e_s. The angles e_s and e_d are clearly analogous to the angle e of the previous section, the subscripts s and d indicating focus at the surface and at depth d, respectively.

---

[4] K. E. Bullen, "An Introduction to the Theory of Seismology", Cambridge University Press, 1947, p. 211.

The surface of an earth stripped to depth d has been indicated in the figure. The extended distance tables[2] for P give a projection on the basis of this stripped earth. If those earlier tables and the present ones are to be compatible the projection must again be on the stripped earth. Then for either PKP or the corresponding PcP the extended position of S is obtained by drawing the tangent FS′ to the seismic ray at F, and continuing it to meet the stripped earth at S′. The extended distance is obtained by projecting on the diametral plane from the point C, and is thus equal to OB. As in the earlier paper, the radius of the stripped earth is taken equal to unity, so that OB = tan e_d. In the theory to be developed it is more convenient to work with the complementary angle i_d, so that

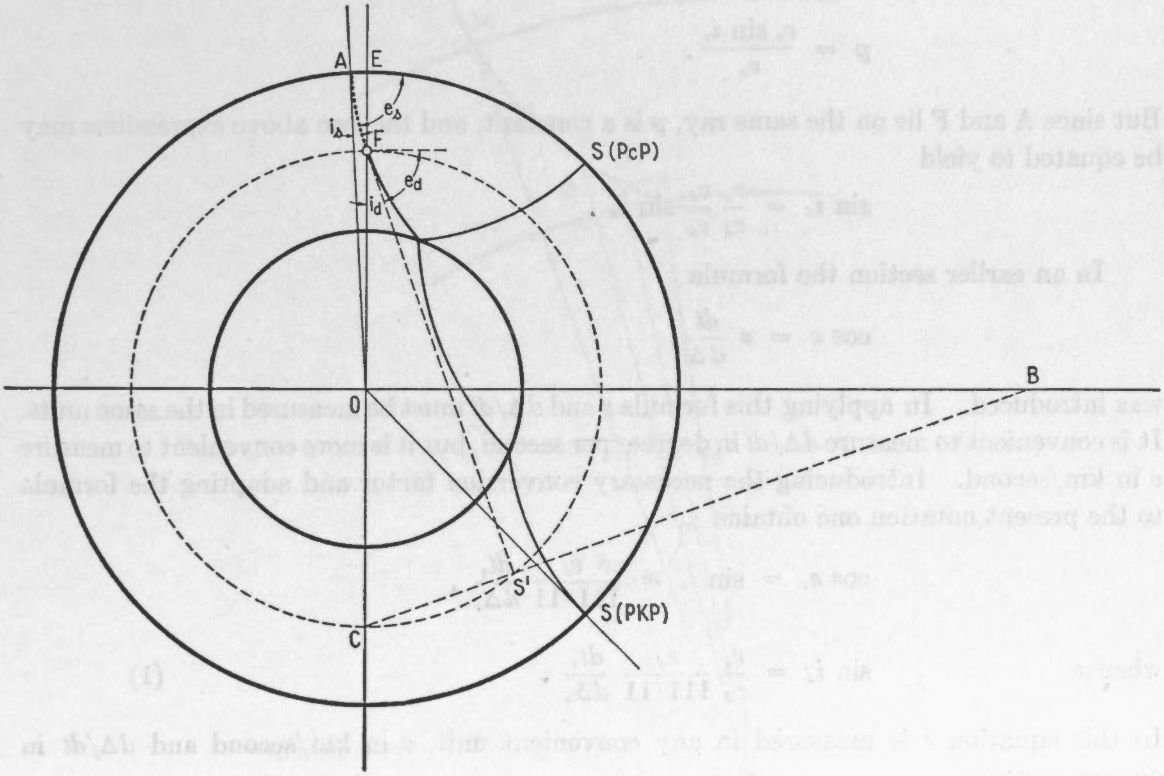


FIGURE 3

$$\text{OB} = \cot i_d .$$

It is now necessary to express i_d in terms of e_s, or its complement i_s, since this can be determined readily from the surface-focus travel-time curve.

It is a well-known property of seismic rays* in a spherically concentric earth, that for any ray the quantity

$$p = \frac{r \sin i}{v}$$

is a constant. p varies of course from ray to ray and may be regarded as a parameter defining the ray. In the above equation r is the distance from the centre of the earth to the

---

* See, for example, reference 4, pp. 108–109.

point on the ray, v is the velocity at that point, and i is the angle between the radius vector and the ray. Applying this equation at the point F one obtains

$$p = \frac{r_d \sin i_d}{v_d},$$

the subscript d indicating the depth of F and i_d being identical with the angle defined in Figure 3. Similarly, at the surface,

$$p = \frac{r_s \sin i_s}{v_s}.$$

But since A and F lie on the same ray, p is a constant, and the two above expressions may be equated to yield

$$\sin i_d = \frac{r_s}{r_d} \frac{v_d}{v_s} \sin i_s \,.$$

In an earlier section the formula

$$\cos e = v \frac{dt}{d\Delta}$$

was introduced. In applying this formula v and $d\Delta/dt$ must be measured in the same units. It is convenient to measure $d\Delta/dt$ in degrees per second, but it is more convenient to measure v in km/second. Introducing the necessary conversion factor and adapting the formula to the present notation one obtains

$$\cos e_s = \sin i_s = \frac{v_s}{111 \cdot 11} \frac{dt_s}{d\Delta_s},$$

whence

$$\sin i_d = \frac{r_s}{r_d} \frac{v_d}{111 \cdot 11} \frac{dt_s}{d\Delta_s} \,. \tag{1}$$

In this equation r is measured in any convenient unit, v in km/second and $d\Delta/dt$ in degrees/second.

One point remains to be discussed: the position of A relative to F. Turning to Figure 3 let the arc distance of ES be called Δ_d, that of AS Δ_s, and that of AE θ_{sd}. Then

$$\Delta_s = \Delta_d + \theta_{sd} \,. \tag{2}$$

In practice the epicentral distance of a station, Δ_d, will be known, but to apply equation (1) it is necessary to determine the slope of the surface-focus travel-time curve at epicentral distance Δ_s. A knowledge of θ_{sd} is essential.

Consider the problem more generally. Let M, N, (Figure 4) be two points on a ray at depths m, n within the earth. It is required to determine the angle subtended at the centre of the earth by this segment of the ray. Let P be a general point on the ray such that MP, of arc length S, subtends an angle θ at the centre. Let an additional small angle $d\theta$ cut off an additional arc dS. Let the radii to M, P and N be r_M, r and r_N respectively. Then in the elementary triangle PQR:

$$\begin{aligned} \text{angle QPR} &= i, \text{ as previously defined,} \\ \text{RQ} &= (r - dr)d\theta \doteq r\, d\theta, \\ \text{PQ} &= dS. \end{aligned}$$

Hence $$\sin i = r \frac{d\theta}{dS}\,.$$

But $$p = \frac{r}{v} \sin i = \frac{r^2}{v} \frac{d\theta}{dS}\,,$$

whence $$dS = \frac{r^2}{pv}\, d\theta\,.$$

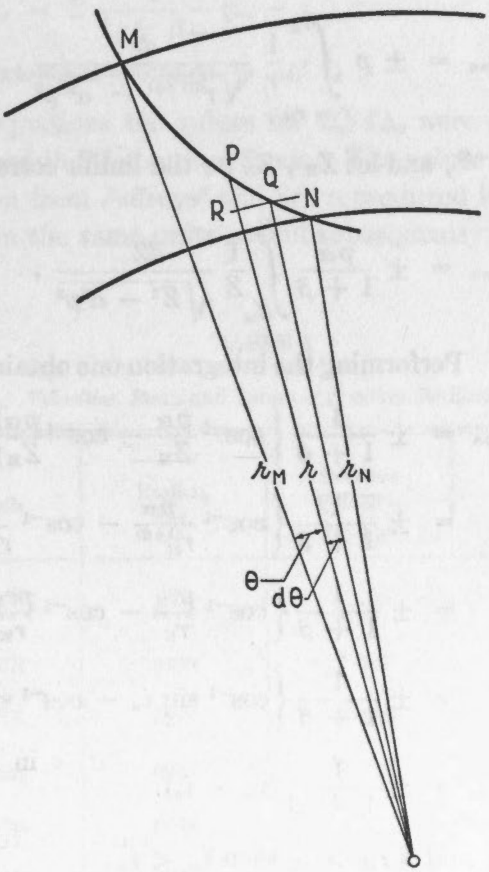


FIGURE 4

From the same triangle

$$dS^2 = dr^2 + r^2\, d\theta^2.$$

Substituting the above value for dS, and simplifying, one obtains

$$d\theta = \pm \frac{p}{r} \frac{dr}{\sqrt{\dfrac{r^2}{v^2} - p^2}}\,.$$

Then the angle subtended by the arc MN is

$$\theta_{mn} = \pm\, p \int_{r = r_M}^{r_N} \frac{1}{r} \frac{dr}{\sqrt{\dfrac{r^2}{v^2} - p^2}}\,.$$

Up to this point the argument has been completely general but it is now necessary to express v as some function of r. For reasons which will be outlined later we propose to assume that v may be expressed in the form

$$v = \alpha r^{-\beta},$$

where α and β are constants. Then the integral assumes the form

$$\theta_{mn} = \pm p \int_{r=r_M}^{r_N} \frac{1}{r} \frac{dr}{\sqrt{r^{2(1+\beta)} - \alpha^2 p^2}}\,.$$

Now, substitute $Z = r^{(1+\beta)}$, and let Z_M, Z_N be the limits corresponding to r_M, r_N. The integral reduces to

$$\theta_{mn} = \pm \frac{p\alpha}{1+\beta} \int_{Z_M}^{Z_N} \frac{1}{Z} \frac{dZ}{\sqrt{Z^2 - \alpha^2 p^2}}\,,$$

which is a standard form. Performing the integration one obtains

$$\begin{aligned}
\theta_{mn} &= \pm \frac{1}{1+\beta}\left\{\cos^{-1}\frac{p\alpha}{Z_N} - \cos^{-1}\frac{p\alpha}{Z_M}\right\},\\
&= \pm \frac{1}{1+\beta}\left\{\cos^{-1}\frac{p\alpha}{r_N^{(1+\beta)}} - \cos^{-1}\frac{p\alpha}{r_M^{(1+\beta)}}\right\},\\
&= \pm \frac{1}{1+\beta}\left\{\cos^{-1}\frac{pv_N}{r_N} - \cos^{-1}\frac{pv_M}{r_M}\right\},\\
&= \pm \frac{1}{1+\beta}\left\{\cos^{-1}\sin i_n - \cos^{-1}\sin i_m\right\},\\
&= \pm \frac{1}{1+\beta}(i_m - i_n).
\end{aligned}$$

But θ_{mn} must be positive, and if $r_M > r_N$ then $i_m < i_n$.
We must write

$$\theta_{mn} = + \frac{1}{1+\beta}(i_n - i_m).$$

The law of velocity distribution assumed, viz.:

$$v = \alpha r^{-\beta},$$

is not likely to fit the facts at all depths for fixed values of α and β. At most it may be hoped that certain values of α and β will describe velocity over a certain range of depth; with different values another section may be described, and so on. Then the total angle subtended by an arc will be made up of a number of sections, each integral being computed with appropriate values of α and β. This may be expressed formally by setting

$$\theta_{sd} = \Sigma \frac{1}{1+\beta_{mn}}(i_n - i_m). \qquad (3)$$

There is no loss of generality in such extension of the analysis.

DERIVATION OF THE TABLES

The following four equations are available from the foregoing analysis:

$$\sin i_d = \frac{r_s}{r_d} \cdot \frac{v_d}{111 \cdot 11} \cdot \frac{dt_s}{d\Delta_s}, \tag{1}$$

$$\Delta_s = \Delta_d + \theta_{sd}\ , \tag{2}$$

$$\theta_{sd} = \Sigma \frac{1}{1 + \beta_{mn}} (i_n - i_m), \tag{3}$$

$$\text{Extended distance} = \cot i_d\ . \tag{4}$$

In applying these equations the values for $dt_s/d\Delta_s$ were obtained from the Jeffreys-Bullen tables[3] for PKP and PcP for surface focus. The values of the P-wave velocities at various depths were taken from Jeffreys[5] and are reproduced in Table I. It will be noted that depth is measured in the same units as will subsequently be used in describing focal depth.

TABLE I

Velocities, Radii and Values of β within the Earth

Depth	Radius, km.	P-Wave Velocity, km/sec.	β
Surface	6371	7·72	0·6723
0·00R	6338	7·747	2·371
0·01R	6275	7·936	2·371
0·02R	6211	8·131	2·371
0·03R	6148	8·332	2·371
0·04R	6084	8·539	2·371
0·05R	6021	8·752	2·371
0·06R	5958	8·971	5·357
0·07R	5894	9·50	3·908
0·08R	5831	9·91	3·176
0·09R	5768	10·26	2·522
0·10R	5704	10·55	1·847
0·11R	5641	10·77	1·790
0·12R	5577	10·99	

---

[5] H. Jeffreys, "Times of P, S and SKS, and Velocities of P and S," *Mon. Not. Royal Astron. Soc., Geophys. Suppl.*, Vol. 4, 498–533, 1939.

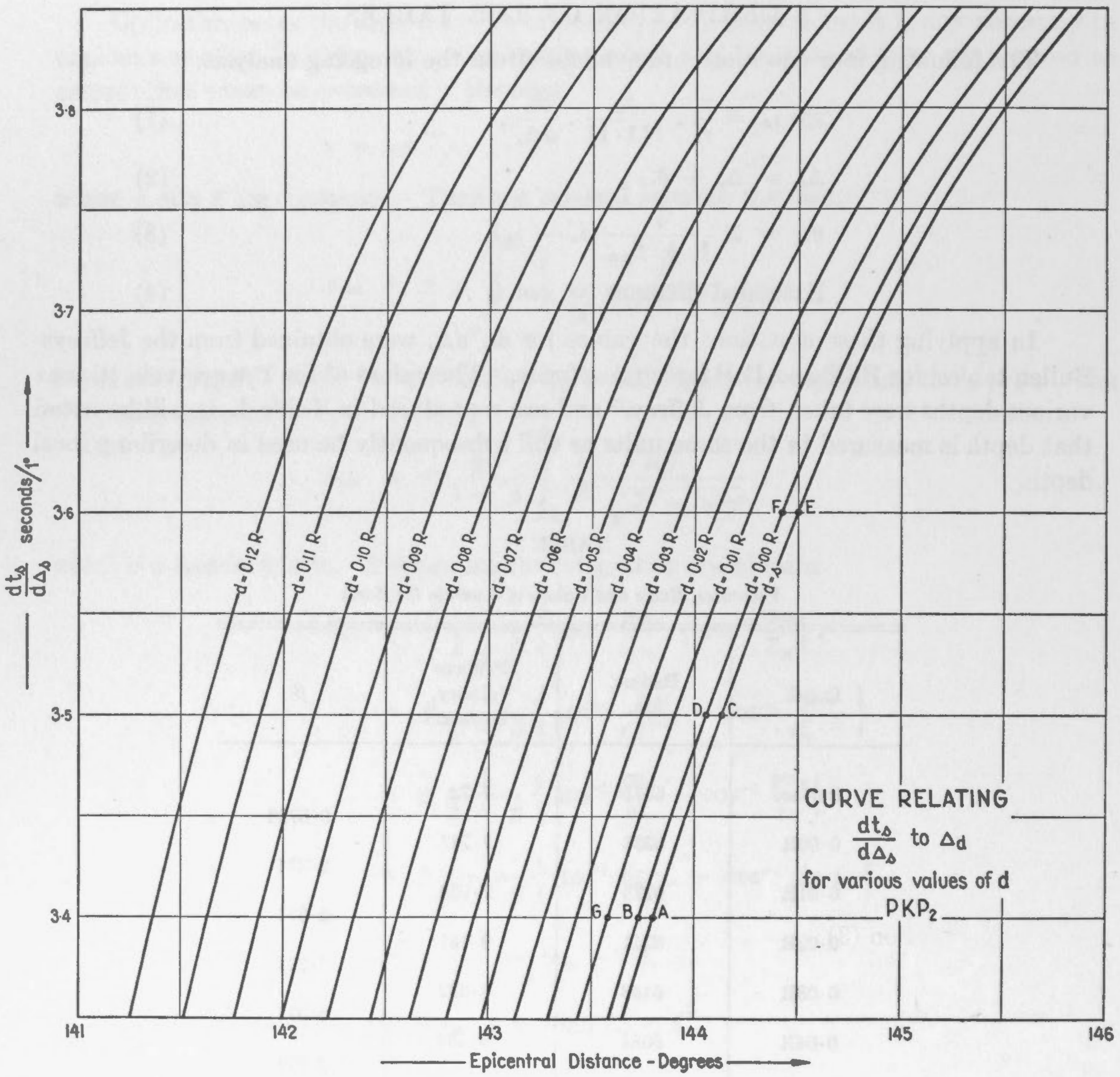


FIGURE 5

Bullen* has pointed out that from a depth of 0.00R to a depth of 0.06R the velocity may be described by the formula.

$$v = \alpha r^{-7/3}.$$

It was this formula which suggested the form of substitution for v in terms of r. The general formula does not apply over any considerable range except this one, but we have assumed that it may be applied over each step of the range, as for example Surface to 0.00R, 0.06R to 0.07R, etc., and have computed the value of β appropriate to each range. These computed values of β are also shown in Table I.

---

* Reference 4 p. 211.

In an earlier section it was shown that the slope of the PKP curve varies between the same limits as does that of PcP, or to put it another way, that a ray which gives rise to any PKP also sets up a PcP. By arranging the computation in terms of rays the work can be much reduced. This was accomplished in the following way. A curve relating Δ_s to the inverse slope $dt_s/d\Delta_s$ was plotted for each of PKP_1, the cusp segment, PKP_2 and PcP. A section of this curve for PKP_2 is shown in Figure 5, labeled $d = s$. For PcP the inverse slope varies from zero to 4.5 seconds/1°, for PKP_1 from zero to 2·0, for the cusp segment from 2.2 to 3.1 and for PKP_2 from 3.1 to 4.5. The range zero to 4.5 seconds/1° therefore covers all the phases. Selecting 45 values of the inverse slope, at intervals of 0·1 sec/1°, was equivalent to selecting 45 rays for consideration.

The method of computation will be illustrated by an example corresponding to the section of the curve illustrated in Figure 5. In the section illustrated $dt_s/d\Delta_s$ varies from 3·35 to 3·85 seconds/1°; the integral values 3·4, 3·5, 3·6, 3·7 and 3·8 are selected for computation.

Taking first of all the value 3·4 and applying equation (1) for $d = s$ one obtains:

$$\begin{aligned} \sin i_s &= \frac{6371}{6371} \times \frac{7{\cdot}72}{111{\cdot}1} \times 3{\cdot}4\,, \\ &= 0{\cdot}2363\,, \\ i_s &= 13^\circ{\cdot}66_6\,. \end{aligned}$$

For convenience write $_0$, $_1$, etc. in place of 0·00R, 0·01R etc. in subscripts. Then

$$\begin{aligned} \sin i_o &= \frac{6371}{6338} \times \frac{7{\cdot}747}{111{\cdot}1} \times 3{\cdot}4\,, \\ &= 0{\cdot}2383\,, \\ i_o &= 13^\circ{\cdot}78_7\,. \end{aligned}$$

Now apply equation (3)

$$\begin{aligned} \theta_{so} &= \frac{1}{1 + 0{\cdot}6723}\,(13^\circ{\cdot}78_7 - 13^\circ{\cdot}66_6)\,, \\ &= 0^\circ{\cdot}07_2\,. \end{aligned}$$

Similarly, taking $dt_s/d\Delta_s$ as 3·5, 3·6 etc., one obtains the values shown in Table II.

TABLE II

Type Computations of θ_{so}

$dt_s/d\Delta_s$ sec/1°	i_s degrees	i_o degrees	θ_{so} degrees
3·4	$13{\cdot}66_6$	$13{\cdot}78_7$	$0{\cdot}07_2$
3·5	$14{\cdot}07_6$	$14{\cdot}20_1$	$0{\cdot}07_5$
3·6	$14{\cdot}48_6$	$14{\cdot}61_6$	$0{\cdot}07_8$
3·7	$14{\cdot}89_8$	$15{\cdot}03_1$	$0{\cdot}08_0$
3·8	$15{\cdot}31_1$	$15{\cdot}44_7$	$0{\cdot}08_1$

With these values of θ_{s0} obtained, return now to Figure 5. On the ordinate corresponding to $dt_s/d\Delta_s$ equal to 3.4, cut off AB equal to the appropriate value of θ_{s0} ($= 0^{\circ}.07_2$). Similarly on the ordinate 3·5 cut off CD $= 0^{\circ}.07_5$, on the ordinate 3·6 cut off EF $= 0^{\circ}.07_8$, and so on. When the series of points BDF . . . is connected, the result is a smooth curve relating epicentral distance for focal depth 0·00R to the slope of the surface travel time curve, for the new curve relates $dt_s/d\Delta_s$ to $\Delta_s - \theta_{s0}$ by construction, and by equation (2)

$$\Delta_s - \theta_{s0} = \Delta_d \,.$$

To construct the tables of extended distances enter this new curve at integral values of epicentral distance, read off the corresponding values of $dt_s/d\Delta_s$, apply equation (1) to obtain $\sin i_d$, and then equation (4) to give extended distance.

At the same time, of course, the values of θ_{s0} obtained in Table II are applied to the PcP curve so that the one set of computations yields data on both PcP and PKP.

Returning to the computations one obtains:

$$\begin{aligned} \sin i_1 &= \frac{6371}{6275} \times \frac{7{\cdot}936}{111{\cdot}1} \times 3{\cdot}4\,, \\ &= 0{\cdot}2466\,, \\ i_1 &= 14^{\circ}.27_6\,, \\ \theta_{01} &= \frac{1}{1 + 2{\cdot}371}\,(14^{\circ}.27_6 - 13^{\circ}.78_7)\,, \\ &= 0^{\circ}.14_5\,. \end{aligned}$$

Then $\theta_{s1} = \theta_{s0} + \theta_{01} = 0^{\circ}.07_2 + 0^{\circ}.14_5 = 0^{\circ}.21_7$.

The distance AG is now cut off $= 0^{\circ}.21_7$ on the ordinate 3·4. Similarly, taking values of $dt_s/d\Delta_s$ equal to 3·5, 3·6 etc. a series of points is obtained; when these are connected by a smooth curve we have a graph relating epicentral distance for depth 0·01R to the slope of the surface travel-time curve. Again, using equation (1), values of i_1 may be obtained for integral values of epicentral distance, and using equation (4), extended distance may be computed.

The computation thus proceeds step by step, each θ that is computed being used to construct the curve for that particular depth, and at the same time contributing its value to the next greater depth. Between 0·00R and 0·06R the effect of accumulative error is eliminated because the same value of β can be used over the entire range.

DISCUSSION

The tables will be found at the end of the paper. Table IV (pages 342 to 343) gives extended distances for PKP_1, Table V (page 344) for the cusp segment, Table VI (page 345) for PKP_2 and Table VII (pages 346 to 348) for PcP. The tables are to be used in conjunction with the earlier ones[2] for P, the projections being compatible in every respect.

In an earlier section it was pointed out that, for surface focus, a ray which just misses the core and so emerges as a P phase at 105°, leaves the focus at nearly the same angle as a PKP_2 emergent at 180° and as a PcP emergent at 100°. Since extended distance is a function of this angle, the extended distance for P at 105° should be only very slightly smaller than that for PKP_2 at 180° and for PcP at 100°. The same sort of relationship should obtain at all focal depths, the last entry for P being approximately the same as the last entry for PcP and the entry for PKP_2 at 180°. This fact affords a check between the present tables and the earlier ones, which is important since the two sets have been derived by quite different methods.

The comparison is provided in Table III. It will be seen that there are no essential differences.

TABLE III

Comparison of Limiting Values of P, PKP_2 and PcP

Depth	Extended Distance		
	P	PKP_2	PcP
Surface	3·066	3·08	3·08
0·00R	3·046	3·05	3·05
0·01R	2·930	2·93	2·93
0·02R	2·820	2·82	2·82
0·03R	2·713	2·71	2·71
0·04R	2·588	2·61	2·61
0·05R	2·485	2·50	2·50
0·06R	2·392	2·40	2·40
0·07R	2·223	2·22	2·22
0·08R	2·085	2·08	2·08
0·09R	1·969	1·96	1·96
0·10R	1·872	1·87	1·87
0·11R	1·800	1·79	1·79
0·12R	1·740	1·72	1·72

TABLE IV

Extended Distances for PKP_1

Δ°	Depth h =													
	Surface	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
109	....	....	....	6·68	6·45	6·22	6·00	5·79	5·40	5·11	4·87	4·68	4·53	4·38
110	7·24	7·17	6·93	6·69	6·46	6·23	6·01	5·80	5·41	5·12	4·88	4·69	4·54	4·39
111	7·25	7·19	6·94	6·70	6·47	6·25	6·03	5·81	5·42	5·13	4·90	4·70	4·55	4·40
112	7·27	7·20	6·96	6·72	6·48	6·26	6·04	5·82	5·43	5·14	4·91	4·71	4·56	4·41
113	7·28	7·22	6·97	6·73	6·50	6·27	6·05	5·84	5·44	5·15	4·92	4·72	4·57	4·42
114	7·30	7·23	6·99	6·75	6·51	6·29	6·06	5·85	5·45	5·16	4·93	4·73	4·58	4·43
115	7·31	7·25	7·00	6·76	6·53	6·30	6·08	5·86	5·47	5·18	4·94	4·74	4·59	4·44
116	7·33	7·27	7·02	6·78	6·54	6·31	6·09	5·88	5·48	5·19	4·95	4·75	4·60	4·45
117	7·34	7·28	7·04	6·79	6·56	6·33	6·11	5·89	5·49	5·20	4·96	4·77	4·61	4·46
118	7·36	7·30	7·05	6·81	6·57	6·34	6·12	5·90	5·50	5·21	4·97	4·78	4·62	4·47
119	7·38	7·32	7·07	6·82	6·59	6·36	6·14	5·92	5·52	5·23	4·99	4·79	4·63	4·48
120	7·40	7·34	7·08	6·84	6·61	6·37	6·15	5·93	5·53	5·24	5·00	4·80	4·64	4·50
121	7·42	7·36	7·10	6·86	6·62	6·39	6·17	5·95	5·55	5·25	5·01	4·81	4·66	4·51
122	7·44	7·37	7·12	6·88	6·64	6·41	6·18	5·96	5·56	5·27	5·02	4·83	4·67	4·52
123	7·46	7·39	7·14	6·89	6·65	6·42	6·20	5·98	5·58	5·28	5·04	4·84	4·69	4·53
124	7·48	7·41	7·16	6·91	6·67	6·44	6·21	6·00	5·59	5·30	5·05	4·86	4·70	4·55
125	7·50	7·43	7·18	6·93	6·69	6·46	6·23	6·01	5·61	5·31	5·07	4·87	4·71	4·56
126	7·52	7·45	7·20	6·95	6·71	6·48	6·25	6·03	5·62	5·33	5·08	4·88	4·73	4·57
127	7·54	7·47	7·22	6·97	6·73	6·50	6·27	6·05	5·64	5·34	5·09	4·90	4·74	4·59
128	7·56	7·49	7·24	6·99	6·75	6·52	6·29	6·07	5·66	5·36	5·11	4·91	4·75	4·60
129	7·59	7·52	7·27	7·01	6·77	6·54	6·31	6·09	5·68	5·38	5·13	4·93	4·77	4·62
130	7·61	7·54	7·29	7·04	6·79	6·56	6·33	6·11	5·70	5·40	5·15	4·94	4·79	4·63
131	7·64	7·57	7·31	7·06	6·81	6·58	6·35	6·13	5·72	5·41	5·16	4·96	4·80	4·65
132	7·66	7·60	7·34	7·09	6·84	6·61	6·38	6·15	5·74	5·44	5·19	4·98	4·82	4·67
133	7·69	7·63	7·37	7·12	6·87	6·63	6·40	6·18	5·76	5·46	5·21	5·01	4·85	4·69
134	7·73	7·66	7·40	7·15	6·90	6.66	6·43	6·21	5·79	5·49	5·23	5·03	4·87	4·72
135	7·77	7·70	7·44	7·19	6·94	6·70	6·46	6·24	5·82	5·51	5·26	5·06	4·90	4·74
136	7·81	7·74	7·48	7·23	6·98	6·73	6·50	6·27	5·85	5·54	5·29	5·09	4·93	4·77
137	7·85	7·79	7·53	7·27	7·02	6·78	6·54	6·31	5·89	5·58	5·33	5·12	4·96	4·81
138	7·91	7·84	7·58	7·32	7·07	6·82	6·59	6·36	5·93	5·62	5·37	5·16	5·00	4·84
139	7·96	7·89	7·63	7·37	7·12	6·88	6·64	6·41	5·98	5·67	5·41	5·20	5·04	4·88
140	8·03	7·96	7·69	7·43	7·18	6·93	6·70	6·46	6·03	5·72	5·46	5·25	5·09	4·93
141	8·10	8·03	7·76	7·50	7·24	7·00	6·76	6·52	6·09	5·77	5·51	5·30	5·13	4·98
142	8·18	8·11	7·84	7·57	7·31	7·06	6·82	6·59	6·15	5·83	5·57	5·36	5·19	5·03
143	8·26	8·19	7·92	7·65	7·39	7·14	6·89	6·66	6·22	5·90	5·63	5·42	5·25	5·09
144	8·35	8·28	8·01	7·74	7·48	7·22	6·98	6·74	6·29	5·97	5·70	5·49	5·32	5·15
145	8·46	8·39	8·11	7·84	7·57	7·32	7·07	6·83	6·38	6·05	5·78	5·56	5·39	5·23
146	8·58	8·51	8·23	7·95	7·69	7·43	7·18	6·93	6·47	6·14	5·87	5·65	5·48	5·31
147	8·71	8·64	8·35	8·08	7·81	7·54	7·29	7·04	6·58	6·24	5·96	5·74	5·57	5·40
148	8·86	8·78	8·49	8·21	7·94	7·68	7·42	7·17	6·70	6·35	6·08	5·85	5·67	5·50
149	9·02	8·95	8·66	8·37	8·10	7·83	7·57	7·31	6·83	6·48	6·20	5·97	5·79	5·62

TABLE IV—Concluded

Extended Distances for PKP_1—Concluded

Δ°	Depth h =													
	Surface	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
150	9·22	9·14	8·84	8·55	8·27	8·00	7·72	7·47	6·98	6·63	6·34	6·11	5·93	5·75
151	9·43	9·35	9·05	8·75	8·46	8·18	7·91	7·64	7·15	6·79	6·49	6·26	6·07	5·89
152	9·66	9·58	9·27	8·97	8·67	8·39	8·11	7·84	7·33	6·96	6·66	6·42	6·22	6·05
153	9·91	9·84	9·52	9·20	8·90	8·61	8·33	8·05	7·53	7·15	6·84	6·59	6·40	6·21
154	10·2	10·1	9·78	9·46	9·16	8·86	8·57	8·28	7·74	7·36	7·04	6·78	6·58	6·39
155	10·5	10·4	10·1	9·75	9·44	9·12	8·83	8·53	7·99	7·58	7·26	7·00	6·79	6·59
156	10·8	10·8	10·4	10·1	9·74	9·42	9·12	8·82	8·25	7·84	7·50	7·23	7·03	6·77
157	11·2	11·1	10·8	10·4	10·1	9·76	9·44	9·14	8·56	8·12	7·78	7·50	7·29	7·08
158	11·7	11·6	11·2	10·8	10·5	10·1	9·81	9·49	8·89	8·45	8·09	7·80	7·58	7·37
159	12·2	12·1	11·7	11·3	10·9	10·6	10·2	9·90	9·27	8·82	8·44	8·14	7·91	7·68
160	12·7	12·6	12·2	11·8	11·4	11·1	10·7	10·3	9·70	9·21	8·82	8·51	8·27	8·04
161	13·3	13·2	12·8	12·4	12·0	11·6	11·2	10·9	10·2	9·66	9·25	8·92	8·67	8·43
162	14·0	13·9	13·4	13·0	12·6	12·2	11·8	11·4	10·7	10·2	9·73	9·39	9·13	8·88
163	14·8	14·7	14·2	13·8	13·3	12·9	12·5	12·1	11·3	10·8	10·3	9·94	9·66	9·39
164	15·7	15·6	15·1	14·6	14·1	13·7	13·2	12·8	12·0	11·4	10·9	10·6	10·3	9·98
165	16·7	16·6	16·1	15·6	15·1	14·6	14·1	13·7	12·8	12·2	11·7	11·3	11·0	10·7
166	17·9	17·8	17·3	16·7	16·2	15·7	15·2	14·7	13·7	13·1	12·5	12·1	11·8	11·4
167	19·3	19·2	18·6	18·0	17·4	16·9	16·3	15·8	14·8	14·1	13·5	13·0	12·7	12·3
168	21·0	20·8	20·1	19·5	18·9	18·3	17·7	17·1	16·1	15·3	14·6	14·1	14·0	13·4
169	22·9	22·7	22·0	21·3	20·6	20·0	19·3	18·7	17·5	16·7	16·0	15·4	15·0	14·6
170	25·2	25.0	24·2	23·5	22·7	22·0	21·3	20·6	19·3	18·4	17·6	17·0	16·5	16·1
171	28·0	27·8	27·0	26·1	25·3	24·5	23·7	23·0	21·5	20·5	19·6	18·9	18·4	17·9
172	31·5	31·3	30·3	29·4	28·4	27·5	26·6	25·8	24·2	23·0	22·1	21·3	20·7	20·1
173	36·0	35·7	34·6	33·5	32·5	31·5	30·5	29·5	27·7	26·3	25·2	24·3	23·6	23·0
174	41·9	41·7	40·5	39·0	37·9	36·8	35·6	34·5	32·3	30·7	29·4	28·4	27·6	26·8
175	50·3	50·0	48·5	46·9	45·5	44·1	42·7	41·3	38·6	36·9	35·2	34·2	33·1	32·3
176	63·1	62·6	60·8	58·7	56·9	55·0	53·3	51·7	48·3	46·0	44·1	42·8	41·5	40·4
177	84·7	83·9	81·1	78·4	76·6	74·0	71·4	68·9	64·4	61·8	59·1	57·5	55·7	54·3
178	127·	126·	123·	119·	116·	112·	109·	105·	98·3	93·3	89·1	87·3	84·6	82·0
179	257·	254·	246·	238·	234·	226·	222·	215·	200·	190·	181·	175·	169·	164·
180	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞

TABLE V

Extended Distances for Cusp Segment

Δ°	Depth h =													
	Surface	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
140	....	....	....	....	....	....	....	....	....	....	....	....	....	....
141	....	....	....	....	....	....	....	....	....	....	....	....	....	2·71
142	....	....	....	....	....	....	....	....	3·38	3·22	3·12	3·03	2·98	2·92
143	4·53	4·52	4·40	4·29	4·18	4·07	3·97	3·87	3·64	3·49	3·37	3·28	3·22	3·16
144	4·91	4·89	4·77	4·64	4·53	4·42	4·31	4·20	3·95	3·79	3·66	3·56	3·49	3·43
145	5·35	5·33	5·20	5·07	4·94	4·82	4·70	4·58	4·32	4·14	4·00	3·89	3·82	3·75
146	5·88	5·85	5·71	5·57	5·42	5·29	5·16	5·03	4·72	4·55	4·39	4·28	4·20	....
147	6·51	6·48	6·32	6·16	6·01	5·86	5·72	5·58	....	....	....	....	....	....

TABLE VI

Extended Distances for PKP_2

Δ°	Depth h =													
	Surface	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
141	....	....	....	....	....	....	....	....	....	....	....	....	....	2·55
142	....	....	....	....	....	....	....	....	3·25	2·98	2·75	2·55	2·38	2·22
143	4·53	4·43	4·20	3·97	3·76	3·56	3·36	3·17	2·88	2·66	2·47	2·31	2·19	2·08
144	4·03	3·97	3·78	3·59	3·41	3·24	3·08	2·92	2·68	2·49	2·34	2·21	2·10	2·00
145	3·74	3·69	3·53	3·37	3·22	3·08	2·94	2·80	2·58	2·41	2·27	2·15	2·05	1·96
146	3·59	3·55	3·39	3·26	3·12	2·99	2·86	2·74	2·52	2·36	2·22	2·11	2·01	1·93
147	3·50	3·46	3·32	3·19	3·06	2·93	2·81	2·69	2·48	2·32	2·18	2·07	1·99	1·90
148	3·43	3·40	3·26	3·13	3·01	2·88	2·76	2·65	2·44	2·29	2·16	2·05	1·96	1·88
149	3·39	3·35	3·22	3·09	2·97	2·85	2·73	2·62	2·41	2·26	2·13	2·03	1·94	1·86
150	3·35	3·31	3·18	3·06	2·94	2·82	2·71	2·59	2·39	2·24	2·12	2·01	1·93	1·85
151	3·32	3·28	3·16	3·03	2·91	2·80	2·68	2·57	2·37	2·22	2·10	2·00	1·91	1·83
152	3·29	3·26	3·13	3·01	2·89	2·78	2·66	2·55	2·36	2·21	2·08	1·98	1·90	1·82
153	3·27	3·23	3·11	2·99	2·87	2·76	2·65	2·54	2·34	2·19	2·07	1·97	1·89	1·81
154	3·25	3·21	3·09	2·97	2·86	2·74	2·63	2·53	2·33	2·18	2·06	1·96	1·88	1·80
155	3·23	3·20	3·08	2·96	2·84	2·73	2·62	2·51	2·32	2·17	2·05	1·95	1·87	1·79
156	3·21	3·18	3·06	2·94	2·83	2·72	2·61	2·50	2·31	2·16	2·04	1·94	1·86	1·78
157	3·20	3·17	3·05	2·93	2·82	2·71	2·60	2·49	2·30	2·15	2·03	1·93	1·85	1·78
158	3·19	3·16	3·04	2·92	2·81	2·70	2·59	2·48	2·29	2·14	2·03	1·93	1·85	1·77
159	3·18	3·14	3·03	2·91	2·80	2·69	2·58	2·47	2·28	2·14	2·02	1·92	1·84	1·76
160	3·16	3·13	3·02	2·90	2·79	2·68	2·57	2·46	2·27	2·13	2·01	1·91	1·83	1·76
161	3·15	3·12	3·01	2·89	2·78	2·67	2·56	2·46	2·27	2·12	2·01	1·91	1·83	1·75
162	3·14	3·11	3·00	2·88	2·77	2·66	2·55	2·45	2·26	2·12	2·00	1·90	1·82	1·75
163	3·14	3·10	2·99	2·88	2·76	2·65	2·55	2·44	2·25	2·11	1·99	1·90	1·82	1·74
164	3·13	3·10	2·98	2·87	2·76	2·65	2·54	2·44	2·25	2·11	1·99	1·89	1·82	1·74
165	3·12	3·09	2·97	2·86	2·75	2·64	2·54	2·43	2·24	2·10	1·99	1·89	1·81	1·74
166	3·12	3·08	2·97	2·85	2·74	2·64	2·53	2·43	2·24	2·10	1·98	1·89	1·81	1·73
167	3·11	3·08	2·96	2·85	2·74	2·63	2·53	2·42	2·24	2·10	1·98	1·88	1·81	1·73
168	3·11	3·07	2·96	2·85	2·74	2·63	2·52	2·42	2·23	2·09	1·98	1·88	1·80	1·73
169	3·10	3·07	2·95	2·84	2·73	2·63	2·52	2·42	2·23	2·09	1·98	1·88	1·80	1·73
170	3·10	3·07	2·95	2·84	2·73	2·62	2·52	2·42	2·23	2·09	1·97	1·88	1·80	1·73
171	3·09	3·06	2·95	2·84	2·73	2·62	2·52	2·41	2·23	2·09	1·97	1·88	1·80	1·73
172	3·09	3·06	2·95	2·83	2·72	2·62	2·51	2·41	2·22	2·09	1·97	1·87	1·80	1·72
173	3·09	3·06	2·94	2·83	2·72	2·62	2·51	2·41	2·22	2·08	1·97	1·87	1·80	1·72
174	3·09	3·06	2·94	2·83	2·72	2·61	2·51	2·41	2·22	2·08	1·97	1·87	1·80	1·72
175	3·08	3·05	2·94	2·83	2·72	2·61	2·51	2·41	2·22	2·08	1·97	1·87	1·79	1·72
176	3·08	3·05	2·94	2·83	2·72	2·61	2·51	2·41	2·22	2·08	1·96	1·87	1·79	1·72
177	3·08	3·05	2·94	2·82	2·72	2·61	2·51	2·40	2·22	2·08	1·96	1·87	1·79	1·72
178	3·08	3·05	2·93	2·82	2·71	2·61	2·50	2·40	2·22	2·08	1·96	1·87	1·79	1·72
179	3·08	3·05	2·93	2·82	2·71	2·61	2·50	2·40	2·22	2·08	1·96	1·87	1·79	1·72
180	3·08	3·05	2·93	2·82	2·71	2·61	2·50	2·40	2·22	2·08	1·96	1·87	1·79	1·72

TABLE VII

Extended Distances for PcP

Δ°	Depth h =													
	Surface	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
0	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
1	151·	150·	144·	137·	133·	127·	121·	117·	109·	104·	98·0	92·4	88·6	85·1
2	75.7	74·7	71·8	69·0	66·7	63·7	60·9	58·8	54·6	51·8	49·0	46·7	45·0	43·2
3	50·5	49·7	48·9	45·9	44·4	42·7	41·1	39·3	36·4	34·4	32·7	31·2	30·0	28·9
4	37·9	37·3	35·9	34·6	33·3	32·0	30·7	29·5	27·4	25·9	24·5	23·5	22·6	21·8
5	30·2	29·8	28·8	27·7	26·6	25·7	24·6	23·6	22·0	20·7	19·7	18·8	18·1	17·4
6	25·2	24·9	24·0	23·1	22·2	21·3	20·5	19·7	18·3	17·3	16·4	15·6	15·0	14·5
7	21·5	21·3	20·5	19·8	19·0	18·2	17·5	16·8	15·6	14·7	14·0	13·4	12·8	12·4
8	18·8	18·6	18·0	17·3	16·6	15·9	15·3	14·7	13·7	12·9	12·2	11·7	11·2	10·8
9	16·7	16·6	15·9	15·4	14·7	14·2	13·6	13·1	12·1	11·5	10·9	10·4	9·98	9·59
10	15·1	14·9	14·4	13·8	13·3	12·8	12·3	11·8	10·9	10·3	9·76	9·33	8·98	8·64
11	13·7	13·6	13·0	12·6	12·1	11·6	11·1	10·6	9·93	9·37	8·89	8·48	8·16	7·85
12	12·6	12·4	12·0	11·5	11·1	10·6	10·2	9·81	9·11	8·58	8·13	7·77	7·47	7·19
13	11·6	11·5	11·1	10·6	10·2	9·83	9·45	9·06	8·41	7·93	7·52	7·18	6·91	6·65
14	10·8	10·7	10·3	9·91	9·52	9·15	8·78	8·43	7·83	7·38	7·01	6·69	6·43	6·19
15	10·1	10·0	9·64	9·27	8·92	8·57	8·22	7·91	7·34	6·92	6·57	6·27	6·04	5·80
16	9·54	9·44	9·09	8·75	8·41	8·09	7·77	7·46	6·94	6·54	6·20	5·93	5·70	5·48
17	9·05	8·95	8·62	8·30	7·98	7·67	7·37	7·08	6·58	6·20	5·88	5·62	5·40	5·20
18	8·61	8·52	8·20	7·89	7·59	7·30	7·01	6·73	6·26	5·89	5·59	5·34	5·13	4·94
19	8·21	8·12	7·82	7·52	7·24	6·96	6·68	6·42	5·96	5·61	5·32	5·08	4·89	4·70
20	7·84	7·76	7·47	7·19	6·91	6·64	6·38	6·12	5·69	5·36	5·08	4·85	4·67	4·48
21	7·51	7·43	7·15	6·88	6·62	6·36	6·11	5·87	5·44	5·13	4·86	4·64	4·46	4·29
22	7·20	7·13	6·86	6·60	6·35	6·10	5·86	5·63	5·22	4·91	4·69	4·45	4·28	4·11
23	6·93	6·86	6·59	6·35	6·10	5·87	5·64	5·41	5·02	4·73	4·48	4·28	4·11	3·95
24	6·68	6·61	6·36	6·11	5·88	5·65	5·43	5·21	4·84	4·55	4·32	4·12	3·96	3·80
25	6·44	6·37	6·14	5·90	5·68	5·46	5·24	5·03	4·67	4·39	4·16	3·97	3·82	3·67
26	6·23	6·16	5·93	5·70	5·48	5·27	5·06	4·86	4·51	4·24	4·02	3·84	3·69	3·55
27	6·03	5·97	5·74	5·53	5·31	5·08	4·90	4·71	4·37	4·11	3·89	3·72	3·57	3·43
28	5·85	5·79	5·57	5·36	5·15	4·95	4·75	4·57	4·23	3·98	3·77	3·60	3·46	3·32
29	5·68	5·62	5·41	5·20	5·00	4·80	4·62	4·43	4·11	3·86	3·66	3·49	3·35	3·22
30	5·52	5·46	5·26	5·06	4·86	4·67	4·49	4·31	3·99	3·75	3·56	3·39	3·26	3·13
31	5·37	5·32	5·12	4·90	4·73	4·55	4·37	4·19	3·88	3·65	3·46	3·30	3·17	3·04
32	5·24	5·18	4·99	4·79	4·61	4·43	4·25	4·08	3·78	3·56	3·37	3·21	3·08	2·96
33	5·10	5·05	4·86	4·67	4·49	4·31	4·14	3·98	3·68	3·46	3·28	3·12	3·00	2·88
34	4·98	4·93	4·74	4·56	4·38	4·21	4·04	3·88	3·59	3·37	3·19	3·04	2·92	2·80
35	4·86	4·81	4·63	4·45	4·27	4·10	3·94	3·78	3·50	3·29	3·11	2·97	2·85	2·74
36	4·75	4·70	4·52	4·34	4·17	4·01	3·85	3·69	3·42	3·22	3·05	2·90	2·79	2·68
37	4·64	4·59	4·42	4·25	4·09	3·93	3·77	3·62	3·35	3·15	2·98	2·84	2·73	2·62
38	4·55	4·50	4·34	4·17	4·01	3·85	3·70	3·55	3·28	3·09	2·92	2·78	2·67	2·56
39	4·47	4·42	4·25	4·09	3·93	3·78	3·63	3·48	3·22	3·03	2·86	2·73	2·62	2·51

TABLE VII—Continued

Extended Distances for PcP—Continued

Δ°	Depth h =													
	Surface	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
40	4·38	4·34	4·18	4·02	3·86	3·71	3·56	3·42	3·16	2·97	2·81	2·68	2·57	2·47
41	4·31	4·26	4·10	3·95	3·79	3·64	3·50	3·36	3·11	2·92	2·76	2·63	2·53	2·42
42	4·24	4·19	4·03	3·88	3·73	3·58	3·44	3·30	3·05	2·87	2·72	2·59	2·48	2·38
43	4·17	4·13	3·97	3·82	3·67	3·53	3·39	3·25	3·01	2·82	2·67	2·55	2·44	2·34
44	4·11	4·07	3·91	3·76	3·62	3·47	3·34	3·20	2·96	2·78	2·63	2·51	2·41	2·31
45	4·05	4·01	3·86	3·71	3·57	3·42	3·29	3·16	2·92	2·74	2·59	2·47	2·37	2·27
46	3·99	3·95	3·80	3·66	3·52	3·38	3·24	3·11	2·88	2·70	2·56	2·43	2·34	2·24
47	3·94	3·90	3·76	3·61	3·47	3·33	3·20	3·07	2·84	2·67	2·52	2·40	2·31	2·21
48	3·89	3·85	3·71	3·57	3·43	3·29	3·16	3·04	2·81	2·63	2·49	2·37	2·28	2·18
49	3·85	3·81	3·67	3·53	3·39	3·26	3·14	3·00	2·77	2·60	2·46	2·34	2·25	2·16
50	3·81	3·77	3·62	3·49	3·35	3·22	3·09	2·97	2·74	2·57	2·43	2·32	2·22	2·13
51	3·77	3·73	3·59	3·45	3·32	3·19	3·06	2·93	2·71	2·55	2·41	2·29	2·20	2·11
52	3·73	3·69	3·55	3·41	3·28	3·15	3·02	2·90	2·68	2·52	2·38	2·27	2·17	2·08
53	3·69	3·65	3·51	3·38	3·25	3·12	2·99	2·87	2·65	2·49	2·36	2·24	2·15	2·06
54	3·65	3·62	3·48	3·35	3·22	3·09	2·97	2·84	2·63	2·47	2·33	2·22	2·13	2·04
55	3·62	3·58	3·45	3·31	3·19	3·06	2·94	2·82	2·60	2·44	2·31	2·20	2·11	2·02
56	3·58	3·55	3·41	3·28	3·16	3·03	2·91	2·79	2·58	2·42	2·28	2·17	2·08	2·00
57	3·55	3·52	3·38	3·25	3·13	3·00	2·88	2·76	2·55	2·39	2·26	2·15	2·06	1·98
58	3·52	3·49	3·35	3·22	3·10	2·98	2·86	2·74	2·53	2·37	2·24	2·13	2·05	1·96
59	3·49	3·46	3·32	3·20	3·07	2·95	2·83	2·72	2·51	2·35	2·22	2·11	2·03	1·94
60	3·46	3·43	3·30	3·17	3·05	2·93	2·81	2·69	2·49	2·33	2·20	2·10	2·01	1·93
61	3·44	3·40	3·27	3·15	3·02	2·90	2·79	2·67	2·47	2·31	2·19	2·08	1·99	1·91
62	3·41	3·37	3·25	3·12	3·00	2·88	2·77	2·65	2·45	2·30	2·17	2·06	1·98	1·90
63	3·39	3·35	3·22	3·10	2·98	2·86	2·75	2·63	2·43	2·28	2·15	2·05	1·96	1·88
64	3·36	3·33	3·20	3·08	2·96	2·84	2·73	2·62	2·41	2·26	2·14	2·04	1·95	1·87
65	3·34	3·31	3·18	3·06	2·94	2·82	2·71	2·60	2·40	2·25	2·13	2·02	1·94	1·86
66	3·32	3·29	3·16	3·04	2·92	2·81	2·70	2·59	2·39	2·24	2·11	2·01	1·93	1·85
67	3·30	3·27	3·15	3·03	2·91	2·79	2·68	2·57	2·37	2·23	2·10	2·00	1·92	1·84
68	3·29	3·25	3·13	3·01	2·90	2·78	2·67	2·56	2·36	2·22	2·09	1·99	1·91	1·83
69	3·27	3·24	3·12	3·00	2·88	2·77	2·66	2·55	2·35	2·21	2·09	1·98	1·90	1·83
70	3·26	3·23	3·11	2·99	2·87	2·76	2·65	2·54	2·34	2·20	2·08	1·98	1·90	1·82
71	3·25	3·21	3·09	2·98	2·86	2·75	2·64	2·53	2·34	2·19	2·07	1·97	1·89	1·81
72	3·24	3·20	3·08	2·97	2·85	2·74	2·63	2·52	2·33	2·18	2·06	1·96	1·88	1·81
73	3·23	3·19	3·07	2·96	2·84	2·73	2·62	2·52	2·32	2·18	2·06	1·96	1·88	1·80
74	3·22	3·18	3·07	2·95	2·84	2·72	2·62	2·51	2·32	2·17	2·05	1·95	1·87	1·80
75	3·21	3·18	3·06	2·94	2·83	2·72	2·61	2·50	2·31	2·17	2·05	1·95	1·87	1·79
76	3·20	3·17	3·05	2·94	2·82	2·71	2·60	2·50	2·31	2·16	2·04	1·94	1·87	1·79
77	3·19	3·16	3·04	2·93	2·82	2·71	2·60	2·49	2·30	2·16	2·04	1·94	1·86	1·79
78	3·19	3·16	3·04	2·92	2·81	2·70	2·59	2·49	2·30	2·15	2·03	1·94	1·86	1·78
79	3·18	3·15	3·03	2·92	2·81	2·70	2·59	2·48	2·29	2·15	2·03	1·93	1·85	1·78

TABLE VII—Concluded

Extended Distances for PcP—Concluded

Δ°	Depth h =													
	Surface	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
80	3·18	3·14	3·03	2·91	2·80	2·69	2·58	2·48	2·29	2·14	2·03	1·93	1·85	1·77
81	3·17	3·14	3·02	2·91	2·80	2·69	2·58	2·47	2·28	2·14	2·02	1·93	1·85	1·77
82	3·16	3·13	3·02	2·90	2·79	2·68	2·57	2·47	2·28	2·14	2·02	1·92	1·84	1·77
83	3·16	3·13	3·01	2·90	2·79	2·68	2·57	2·47	2·27	2·13	2·01	1·92	1·84	1·76
84	3·15	3·12	3·00	2·89	2·78	2·67	2·56	2·46	2·27	2·13	2·01	1·91	1·84	1·76
85	3·15	3·12	3·00	2·89	2·78	2·67	2·56	2·46	2·27	2·12	2·01	1·91	1·83	1·76
86	3·14	3·11	2·99	2·88	2·77	2·66	2·56	2·45	2·26	2·12	2·00	1·91	1·83	1·75
87	3·14	3·11	2·99	2·88	2·77	2·66	2·55	2·45	2·26	2·12	2·00	1·90	1·82	1·75
88	3·13	3·10	2·99	2·87	2·76	2·65	2·55	2·44	2·25	2·11	2·00	1·90	1·82	1·75
89	3·13	3·10	2·98	2·87	2·76	2·65	2·54	2·44	2·25	2·11	1·99	1·90	1·82	1·74
90	3·12	3·09	2·98	2·86	2·75	2·64	2·54	2·44	2·25	2·11	1·99	1·89	1·82	1·74
91	3·12	3·09	2·97	2·86	2·75	2·64	2·53	2·43	2·24	2·10	1·99	1·89	1·81	1·74
92	3·11	3·08	2·97	2·85	2·74	2·64	2·53	2·43	2·24	2·10	1·98	1·89	1·81	1·73
93	3·11	3·08	2·96	2·85	2·74	2·63	2·53	2·42	2·24	2·10	1·98	1·88	1·81	1·73
94	3·10	3·07	2·96	2·85	2·74	2·63	2·52	2·42	2·23	2·09	1·98	1·88	1·80	1·73
95	3·10	3·07	2·95	2·84	2·73	2·62	2·52	2·42	2·23	2·09	1·97	1·88	1·80	1·72
96	3·09	3·06	2·95	2·84	2·73	2·62	2·51	2·41	2·22	2·08	1·97	1·87	1·80	1·72
97	3·09	3·06	2·94	2·83	2·72	2·62	2·51	2·41	2·22	2·08	1·97	1·87	1·79	1·72
98	3·08	3·06	2·94	2·83	2·72	2·61	2·51	2·41	2·22	2·08	1·96	....	....	....
99	3·08	3·05	2·94	2·82	2·71	2·61	2·50	2·40	....	....	....	....	....	....
100	3·08	3·05	2·93	2·82	....	....	....	....	....	....	....	....	....	....

[illegible]

CANADA

DEPARTMENT OF MINES AND TECHNICAL SURVEYS

DOMINION OBSERVATORIES

PUBLICATIONS

OF THE

Dominion Observatory

OTTAWA

Vol. XVI No. 11

TABLES OF EXTENDED DISTANCES [illegible]

CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
DOMINION OBSERVATORIES

PUBLICATIONS

OF THE

Dominion Observatory

OTTAWA

VOL. XVI No. 11

TABLES OF EXTENDED DISTANCES FOR PP AND pP

BY

J. H. HODGSON AND J. F. J. ALLEN

EDMOND CLOUTIER, C.M.G., O.A., D.S.P.
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
OTTAWA, 1954

Tables of Extended Distances for PP and pP

BY

J. H. HODGSON AND J. F. J. ALLEN

ABSTRACT

This paper is the third in a series extending Byerly's method of determining the direction of faulting in an earthquake to deep focus earthquakes and permitting the use of secondary P phases. Here tables of extended distances are presented for the reflected rays of PP and pP, for earthquakes of all focal depths down to 0·12 R. The tables are consistent with earlier ones for P, PKP, and PcP, so that the several phases can be used in a single solution.

INTRODUCTION

In carrying out solutions for the direction of faulting in earthquakes, one is frequently handicapped by the scarcity of stations, or by the poor distribution of stations which are available. For this reason it becomes desirable to make as much use as possible of secondary arrivals because these phases, having left the focus at different angles from the first arriving phases, provide points on the projection at the same azimuth but usually at quite different extended distances. Tables for the secondary phases PcP and PKP_2 have already been published[1] and it is the purpose of this paper to present tables of extended distances for the phases PP and pP which involve reflections from the earth's surface in the manner indicated in Figure 2.

DERIVATION OF THE TABLES

These tables of extended distances for PP and pP have been obtained from the tables of extended distances already published[2] for P.

To understand the method of derivation refer to Figure 1, which is reproduced from Figure 1 of the earlier paper[2]. In the figure the ray AFF′B is supposed to be a continuous one. It is the path that would be followed by a P wave travelling between the points A and B. Under these circumstances it was shown that A and B would receive initial P impulses of the same sign, that is either both compressional or both dilatational, from an earthquake occuring at F. The extended distances of points such as A were thus shown in the tables as equal to the extended distances of the related points, such as B, with a negative sign indicating an opposite azimuth.

Pairs of related points, such as A and B, may be selected very simply from the tables by finding pairs of values of extended distances which differ only in sign. For example,

---

[1] J. H. Hodgson and J. F. J. Allen, "Tables of Extended Distances for PKP and PcP", *Publications of the Dominion Observatory, Vol. XVI, No. 10, 1954.*

[2] J. H. Hodgson and R. S. Storey, "Tables Extending Byerly's Fault Plane Techniques to Earthquakes of any Focal Depth", *Bull. Seism. Soc. Am.*, Vol. 43, 49–61, 1953.

assuming a focal depth of 0·12 R, we note that the extended distance for 4°0 is −1·341. By interpolation, the extended distance for 76°1 is +1·341. Then epicentral distances of 4°0 and 76°1 define a pair of related points.

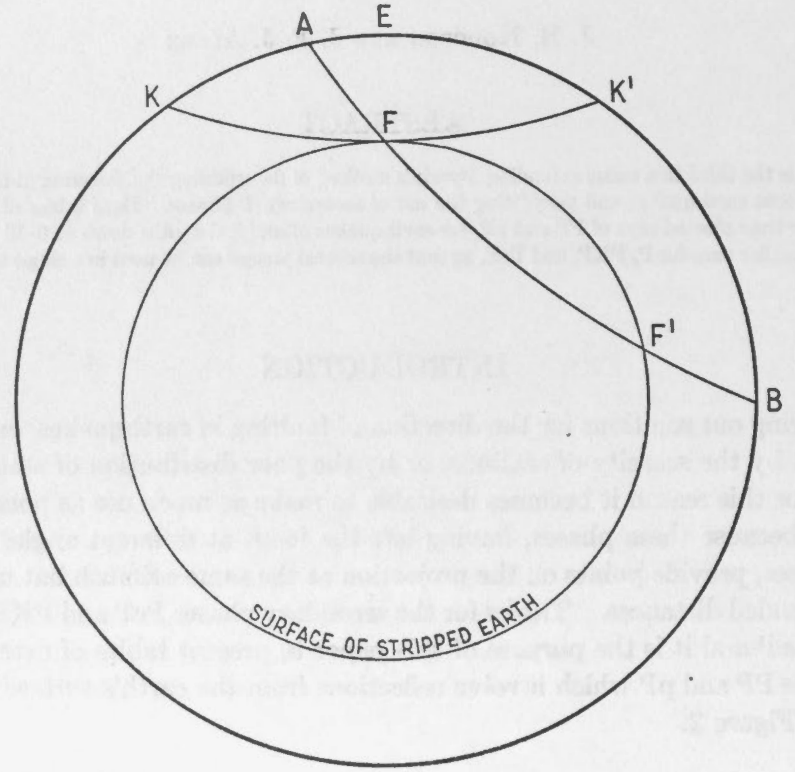


Figure 1.

Before leaving Figure 1 some mention should be made of the ray KFK′ drawn tangential to the stripped earth at the focus F. This ray is important in defining the phases pP and PP. By definition rays, such as FA, rising above it, give rise by reflection at the earth's surface to pP phases; rays, such as FB, falling below it, give rise by reflection to PP phases. The reflected phases generated by the ray KFK′ represent the limiting case where pP and PP are the same.

Now consider Figure 2. The ray AFB of this figure is analagous to the ray AFB of Figure 1, A and B being related points. Then the extended distances of A and B have the same absolute value but opposite signs. The ray FB not only gives rise to a P phase at B but also, by reflection, to a PP phase at C. Since extended distance is a function only of the angle at which the ray leaves the focus, these two phases must have the same extended distance. Similarly a P phase recorded at A and a pP phase recorded at D have the same extended distance; as we have seen it is the negative of the extended distance of a P phase at B. To determine one of these extended distances is to determine them all and it only remains to determine the relative epicentral distances of the points A, B, C and D.

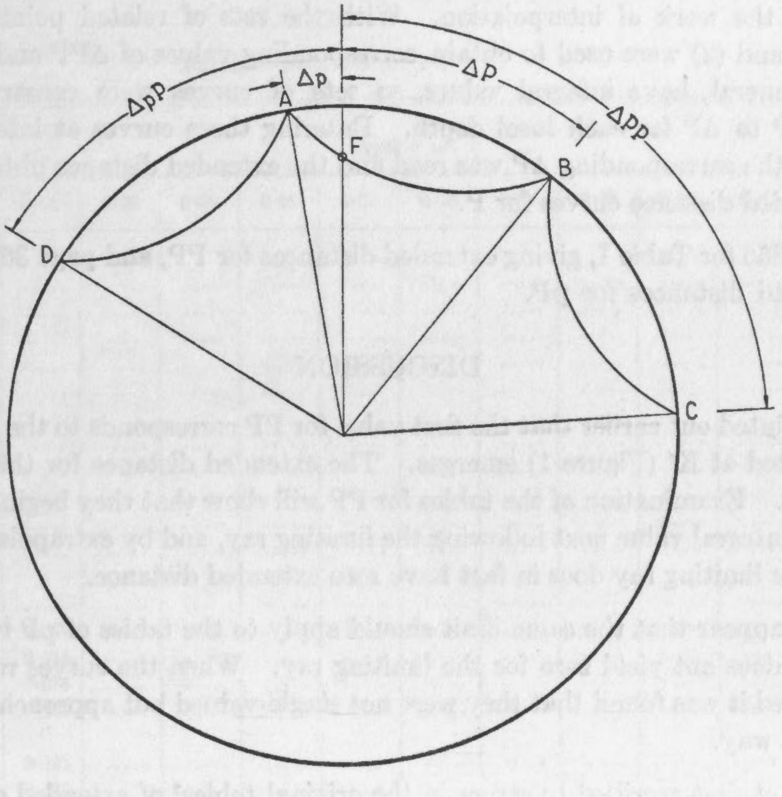


FIGURE 2.

Let these points have the epicentral distances shown in the figure. Then, by inspection, we may write immediately:

$$\Delta PP = 2\Delta P + \Delta p \ldots\ldots\ldots\ldots\ldots (1)$$
$$\Delta pP = \Delta P + 2\Delta p \ldots\ldots\ldots\ldots\ldots (2)$$

The application of these equations to the pair of related points already determined, will illustrate their use. For focal depth 0·12 R we had $\Delta P = 76\overset{\circ}{.}1$, $\Delta p = 4\overset{\circ}{.}0$, with a common extended distance of 1·341

$$\text{Then } \Delta PP = 152\overset{\circ}{.}2 + 4\overset{\circ}{.}0 = 156\overset{\circ}{.}2$$
$$\Delta pP = 76{\cdot}1 + 8\overset{\circ}{.}0 = 84\overset{\circ}{.}1$$

Then, the extended distance for P at $76\overset{\circ}{.}1 = +1{\cdot}341$,
the extended distance for PP at $156\overset{\circ}{.}2 = +1{\cdot}341$,
the extended distance for P at $4\overset{\circ}{.}0 = -1{\cdot}341$,
and the extended distance for pP at $84\overset{\circ}{.}1 = -1{\cdot}341$.

The first step in derivation of the tables was to determine sets of related epicentral distances ΔP and Δp. This was accomplished in the manner outlined above except that the curves from which the tables[2] were derived were used instead of the tables themselves.

This reduced the work of interpolation. With the sets of related points determined, equations (1) and (2) were used to obtain corresponding values of ΔPP and ΔpP. These did not, in general, have integral values, so sets of curves were constructed relating ΔPP and ΔpP to ΔP for each focal depth. Entering these curves at integral values of ΔPP or ΔpP, the corresponding ΔP was read and the extended distance obtained from the original extended distance curves for P.

See page 355 for Table I, giving extended distances for PP, and page 360 for Table II, giving extended distances for pP.

DISCUSSION

It was pointed out earlier that the first value for PP corresponds to the point at which a phase reflected at K′ (Figure 1) emerges. The extended distance for this phase will of course be zero. Examination of the tables for PP will show that they begin, for each focal depth, at the integral value next following the limiting ray, and by extrapolation it may be shown that the limiting ray does in fact have zero extended distance.

It would appear that the same limit should apply to the tables of pP but in this case extrapolation does not yield zero for the limiting ray. When the curves relating ΔpP to ΔP were plotted it was found that they were not single-valued but approached the limit in a most erratic way.

This was at first ascribed to errors in the original tables[2] of extended distance for P. It was thought that the method used in derivation of those tables was less accurate than that developed later for use with PKP. To test this, the latter method was applied to the P data over the complete range of focal depth and over a considerable range of epicentral distance. It was found that the two methods gave results which never differed by more than 1 per cent. Apparently the multiple values in the $\Delta pP - \Delta P$ curve were real. It was concluded that they must indicate a complicated cusp on the pP curve.

We have investigated this matter in some detail and find that there are actually two cusps present in the pP curve. One of them is analagous to the 20° cusp on the P curve. The other occurs at the very beginning of the pP curve. It is due to the fact that the point of emergence of pP, for rays rising above the tangent ray but close to it, is at less epicentral distance than the point of emergence of the pP due to the tangent ray. The extent of the cusp, and the range of angle of the generating ray contributing to it, varies with focal depth but as the depth of focus increases the two cusps come together and interact in a most complicated fashion.

A full description of the phenomenon is reserved for a separate paper. It is sufficient for the present investigation to note that the failure of the pP extended distances to extrapolate smoothly to zero at the point of emergence of the tangent ray is reasonable.

The tables presented herewith are to be used in conjunction with the earlier ones [1, 2], the projections being compatible.

TABLE I

Extended Distances for PP

Δ°	*Depth h =*													
	Surface	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
0	0·000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
1	0·021	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
2	0·042	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
3	0·061	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4	0·077	0·004	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
5	0·093	0·031	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
6	0·108	0·052	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
7	0·122	0·077	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
8	0·135	0·096	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
9	0·148	0·113	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
10	0·160	0·130	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
11	0·173	0·148	0·007	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
12	0·186	0·165	0·044	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
13	0·201	0·181	0·076	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
14	0·215	0·197	0·100	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
15	0·231	0·213	0·123	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
16	0·246	0·230	0·145	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
17	0·262	0·245	0·162	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
18	0·278	0·261	0·181	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
19	0·294	0·278	0·198	0·034	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
20	0·309	0·294	0·215	0·081	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
21	0·325	0·310	0·234	0·122	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
22	0·341	0·327	0·250	0·149	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
23	0·357	0·343	0·267	0·178	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
24	0·374	0·360	0·287	0·201	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
25	0·389	0·375	0·303	0·223	0·091	.....	.....	.....	.....	.....	.....	.....	.....	.....
26	0·406	0·391	0·320	0·244	0·133	.....	.....	.....	0·031	.....	.....	.....	.....	.....
27	0·422	0·407	0·336	0·264	0·166	.....	.....	.....	0·083	.....	.....	.....	.....	.....
28	0·437	0·422	0·353	0·281	0·195	0·056	.....	.....	0·117	.....	.....	.....	.....	.....
29	0·453	0·438	0·373	0·300	0·222	0·108	.....	0·010	0·159	.....	.....	.....	.....	.....
30	0·470	0·453	0·390	0·320	0·244	0·144	.....	0·045	0·190	.....	.....	.....	.....	.....
31	0·487	0·470	0·409	0·336	0·264	0·180	0·019	0·328	0·220	.....	.....	.....	.....	.....
32	0·504	0·487	0·428	0·357	0·284	0·206	0·064	0·409	0·248	.....	.....	.....	.....	.....
33	0·524	0·506	0·449	0·379	0·311	0·236	0·115	0·453	0·277	0·060	.....	.....	.....	.....
34	0·544	0·526	0·476	0·401	0·341	0·290	0·502	0·485	0·305	0·115	.....	.....	.....	.....
35	0·567	0·548	0·503	0·434	0·385	0·503	0·545	0·511	0·332	0·163	.....	.....	.....	.....
36	0·593	0·575	0·539	0·481	0·515	0·613	0·579	0·537	0·359	0·208	.....	.....	.....	.....
37	0·626	0·610	0·585	0·558	0·679	0·649	0·602	0·560	0·385	0·240	0·090	.....	.....	.....
38	0·672	0·659	0·660	0·733	0·718	0·676	0·626	0·578	0·411	0·270	0·140	.....	.....	.....
39	0·742	0·756	0·754	0·789	0·747	0·700	0·645	0·598	0·435	0·303	0·183	.....	.....	.....

TABLE I *(Continued)*

Extended Distances for PP

Δ°	*Depth h =*													
	Surface	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
40	0·840	0·850	0·846	0·821	0·776	0·724	0·666	0·615	0·459	0·334	0·217	0·044	.....	.....
41	0·920	0·910	0·887	0·850	0·797	0·742	0·683	0·634	0·478	0·359	0·249	0·122	.....	.....
42	0·966	0·952	0·916	0·871	0·815	0·758	0·699	0·649	0·500	0·382	0·280	0·166	.....	.....
43	1·001	0·982	0·942	0·890	0·832	0·777	0·719	0·665	0·517	0·405	0·304	0·205	.....	.....
44	1·028	1·007	0·963	0·908	0·852	0·792	0·733	0·679	0·538	0·425	0·329	0·233	0·064	.....
45	1·050	1·030	0·981	0·925	0·868	0·805	0·707	0·696	0·554	0·445	0·349	0·255	0·121	.....
46	1·070	1·050	0·999	0·940	0·883	0·819	0·760	0·710	0·572	0·462	0·365	0·276	0·158	0·015
47	1·088	1·067	1·015	0·955	0·898	0·832	0·774	0·724	0·586	0·480	0·382	0·294	0·185	0·070
48	1·104	1·084	1·030	0·969	0·912	0·845	0·786	0·739	0·600	0·497	0·399	0·310	0·211	0·105
49	1·120	1·100	1·045	0·982	0·925	0·862	0·800	0·750	0·616	0·510	0·411	0·326	0·231	0·135
50	1·135	1·115	1·059	0·996	0·939	0·875	0·812	0·763	0·629	0·526	0·424	0·339	0·253	0·166
51	1·150	1·129	1·072	1·010	0·951	0·887	0·824	0·775	0·641	0·539	0·438	0·353	0·270	0·187
52	1·163	1·144	1·086	1·024	0·964	0·900	0·837	0·787	0·652	0·550	0·451	0·364	0·285	0·208
53	1·177	1·156	1·099	1·035	0·975	0·913	0·850	0·798	0·665	0·564	0·462	0·376	0·301	0·227
54	1·190	1·171	1·111	1·048	0·987	0·925	0·860	0·808	0·675	0·574	0·475	0·386	0·315	0·243
55	1·203	1·185	1·123	1·060	0·999	0·939	0·872	0·818	0·685	0·584	0·484	0·399	0·326	0·260
56	1·216	1·197	1·135	1·071	1·010	0·950	0·883	0·827	0·697	0·594	0·493	0·409	0·336	0·271
57	1·227	1·210	1·146	1·082	1·020	0·960	0·893	0·838	0·707	0·605	0·504	0·420	0·347	0·284
58	1·238	1·221	1·157	1·094	1·031	0·970	0·902	0·847	0·716	0·614	0·511	0·429	0·355	0·295
59	1·250	1·233	1·169	1·104	1·041	0·979	0·913	0·855	0·725	0·623	0·520	0·437	0·366	0·307
60	1·259	1·245	1·179	1·115	1·053	0·988	0·922	0·864	0·733	0·631	0·530	0·446	0·375	0·319
61	1·269	1·255	1·189	1·125	1·062	0·997	0·931	0·871	0·743	0·641	0·537	0·456	0·384	0·328
62	1·279	1·265	1·200	1·134	1·072	1·005	0·939	0·879	0·750	0·647	0·545	0·465	0·394	0·340
63	1·290	1·276	1·210	1·144	1·081	1·014	0·946	0·885	0·759	0·655	0·552	0·472	0·400	0·350
64	1·299	1·285	1·219	1·153	1·090	1·022	0·955	0·892	0·766	0·663	0·560	0·481	0·410	0·360
65	1·308	1·295	1·228	1·162	1·099	1·030	0·965	0·899	0·774	0·670	0·568	0·488	0·417	0·370
66	1·317	1·304	1·237	1·170	1·107	1·039	0·972	0·905	0·780	0·676	0·575	0·495	0·425	0·378
67	1·326	1·314	1·246	1·179	1·115	1·047	0·980	0·912	0·787	0·681	0·582	0·504	0·433	0·387
68	1·335	1·325	1·255	1·187	1·123	1·055	0·986	0·920	0·794	0·687	0·589	0·510	0·440	0·395
69	1·344	1·333	1·263	1·195	1·130	1·066	0·993	0·925	0·800	0·695	0·597	0·517	0·446	0·404
70	1·353	1·341	1·271	1·202	1·138	1·070	1·000	0·931	0·808	0·700	0·604	0·525	0·454	0·411
71	1·360	1·349	1·279	1·210	1·145	1·077	1·006	0·938	0·814	0·706	0·610	0·531	0·460	0·420
72	1·368	1·356	1·287	1·217	1·153	1·084	1·012	0·944	0·820	0·712	0·616	0·538	0·467	0·427
73	1·375	1·364	1·295	1·225	1·160	1·091	1·020	0·950	0·826	0·718	0·623	0·545	0·475	0·436
74	1·382	1·371	1·302	1·231	1·167	1·098	1·026	0·956	0·832	0·725	0·630	0·552	0·481	0·444
75	1·390	1·378	1·309	1·238	1·174	1·105	1·034	0·962	0·838	0·730	0·638	0·559	0·489	0·451
76	1·396	1·385	1·316	1·245	1·181	1·112	1·040	0·969	0·843	0·736	0·645	0·566	0·495	0·459
77	1·403	1·391	1·323	1·251	1·187	1·119	1·047	0·975	0·849	0·743	0·650	0·574	0·503	0·466
78	1·410	1·398	1·330	1·259	1·194	1·125	1·054	0·982	0·855	0·750	0·659	0·580	0·510	0·475
79	1·416	1·405	1·337	1·265	1·200	1·132	1·060	0·990	0·860	0·757	0·666	0·588	0·519	0·482

TABLE I *(Continued)*

Extended Distances for PP

Δ°	*Depth h =*													
	Surface	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
80	1·422	1·411	1·344	1·273	1·207	1·139	1·067	0·996	0·866	0·764	0·672	0·595	0·526	0·490
81	1·429	1·418	1·350	1·280	1·214	1·145	1·075	1·003	0·874	0·770	0·680	0·605	0·534	0·499
82	1·435	1·425	1·359	1·287	1·220	1·152	1·082	1·010	0·880	0·777	0·688	0·611	0·543	0·508
83	1·441	1·431	1·365	1·294	1·227	1·160	1·090	1·017	0·887	0·784	0·696	0·620	0·550	0·515
84	1·448	1·437	1·371	1·300	1·234	1·166	1·098	1·024	0·894	0·791	0·704	0·628	0·560	0·525
85	1·455	1·444	1·377	1·308	1·241	1·174	1·105	1·031	0·900	0·800	0·711	0·635	0·567	0·534
86	1·461	1·451	1·385	1·315	1·248	1·181	1·113	1·038	0·907	0·807	0·719	0·644	0·575	0·543
87	1·469	1·459	1·391	1·322	1·255	1·190	1·120	1·046	0·914	0·815	0·728	0·654	0·586	0·551
88	1·476	1·466	1·398	1·330	1·263	1·198	1·126	1·053	0·923	0·822	0·735	0·662	0·595	0·561
89	1·484	1·474	1·405	1·338	1·271	1·206	1·136	1·061	0·930	0·830	0·744	0·670	0·604	0·570
90	1·492	1·481	1·412	1·345	1·280	1·214	1·145	1·070	0·938	0·838	0·751	0·679	0·615	0·580
91	1·500	1·490	1·420	1·354	1·287	1·221	1·152	1·078	0·946	0·846	0·760	0·689	0·623	0·589
92	1·509	1·498	1·428	1·362	1·295	1·230	1·160	1·088	0·955	0·855	0·770	0·698	0·633	0·600
93	1·519	1·506	1·435	1·371	1·304	1·239	1·169	1·096	0·963	0·864	0·779	0·707	0·645	0·609
94	1·527	1·515	1·444	1·380	1·313	1·247	1·178	1·105	0·972	0·872	0·788	0·716	0·654	0·620
95	1·536	1·525	1·452	1·389	1·322	1·255	1·186	1·115	0·980	0·883	0·797	0·725	0·664	0·629
96	1·546	1·535	1·461	1·398	1·330	1·265	1·195	1·123	0·990	0·893	0·806	0·736	0·675	0·640
97	1·556	1·544	1·471	1·408	1·340	1·274	1·205	1·132	1·001	0·902	0·817	0·746	0·685	0·650
98	1·566	1·554	1·480	1·417	1·349	1·284	1·215	1·144	1·011	0·911	0·827	0·756	0·695	0·660
99	1·576	1·564	1·490	1·427	1·359	1·293	1·224	1·154	1·020	0·920	0·836	0·765	0·707	0·671
100	1·587	1·574	1·500	1·437	1·369	1·303	1·234	1·164	1·030	0·931	0·846	0·775	0·717	0·681
101	1·598	1·585	1·511	1·447	1·380	1·314	1·245	1·174	1·041	0·943	0·856	0·787	0·728	0·691
102	1·609	1·595	1·521	1·458	1·390	1·324	1·255	1·185	1·051	0·953	0·866	0·798	0·740	0·704
103	1·620	1·606	1·533	1·471	1·401	1·334	1·265	1·195	1·062	0·964	0·877	0·808	0·752	0·715
104	1·631	1·618	1·544	1·481	1·411	1·344	1·276	1·205	1·075	0·974	0·890	0·820	0·763	0·725
105	1·643	1·629	1·555	1·493	1·422	1·355	1·286	1·215	1·085	0·985	0·900	0·830	0·774	0·735
106	1·654	1·640	1·567	1·504	1·434	1·367	1·297	1·228	1·095	0·995	0·910	0·841	0·784	0·748
107	1·666	1·653	1·579	1·515	1·445	1·379	1·308	1·239	1·106	1·005	0·920	0·854	0·795	0·758
108	1·679	1·665	1·590	1·526	1·455	1·390	1·321	1·250	1·118	1·019	0·931	0·864	0·806	0·768
109	1·690	1·677	1·602	1·539	1·467	1·401	1·332	1·260	1·129	1·030	0·941	0·875	0·816	0·780
110	1·704	1·689	1·615	1·550	1·479	1·413	1·343	1·272	1·140	1·040	0·952	0·885	0·828	0·790
111	1·715	1·702	1·627	1·562	1·490	1·425	1·355	1·284	1·150	1·051	0·965	0·898	0·840	0·800
112	1·727	1·714	1·640	1·574	1·502	1·436	1·366	1·295	1·161	1·063	0·976	0·909	0·850	0·814
113	1·740	1·727	1·652	1·585	1·514	1·448	1·377	1·305	1·175	1·074	0·986	0·919	0·862	0·824
114	1·754	1·740	1·665	1·597	1·526	1·460	1·389	1·317	1·185	1·085	0·996	0·930	0·872	0·834
115	1·767	1·752	1·678	1·610	1·538	1·471	1·400	1·328	1·197	1·098	1·007	0·942	0·885	0·846
116	1·780	1·766	1·690	1·622	1·550	1·483	1·411	1·340	1·208	1·110	1·020	0·953	0·895	0·856
117	1·794	1·780	1·703	1·634	1·562	1·495	1·423	1·350	1·219	1·120	1·030	0·964	0·905	0·867
118	1·808	1·793	1·716	1·646	1·575	1·507	1·435	1·362	1·230	1·131	1·041	0·974	0·917	0·880
119	1·823	1·807	1·730	1·659	1·586	1·519	1·446	1·375	1·241	1·143	1·051	0·985	0·930	0·890

TABLE I *(Continued)*

Extended Distances for PP

Δ°	Depth *h* =													
	Surface	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
120	1·837	1·821	1·743	1·671	1·599	1·530	1·459	1·386	1·255	1·155	1·063	0·997	0·940	0·900
121	1·850	1·835	1·756	1·685	1·611	1·542	1·470	1·400	1·266	1·165	1·075	1·008	0·951	0·911
122	1·864	1·849	1·770	1·698	1·625	1·555	1·482	1·410	1·278	1·176	1·085	1·018	0·963	0·922
123	1·879	1·863	1·786	1·711	1·639	1·566	1·494	1·424	1·290	1·187	1·097	1·029	0·974	0·934
124	1·892	1·877	1·800	1·725	1·650	1·579	1·506	1·435	1·300	1·200	1·108	1·040	0·984	0·945
125	1·906	1·892	1·814	1·738	1·663	1·593	1·517	1·447	1·312	1·211	1·119	1·052	0·994	0·956
126	1·922	1·907	1·828	1·750	1·675	1·605	1·530	1·459	1·325	1·222	1·130	1·063	1·004	0·968
127	1·936	1·921	1·841	1·764	1·689	1·617	1·540	1·471	1·335	1·234	1·140	1·073	1·015	0·980
128	1·951	1·936	1·856	1·778	1·701	1·630	1·553	1·484	1·348	1·245	1·155	1·084	1·025	0·990
129	1·965	1·951	1·870	1·792	1·714	1·643	1·567	1·495	1·361	1·255	1·166	1·095	1·036	1·001
130	1·980	1·965	1·885	1·806	1·727	1·655	1·580	1·510	1·373	1·267	1·177	1·105	1·046	1·012
131	1·995	1·981	1·900	1·819	1·740	1·668	1·592	1·523	1·385	1·279	1·189	1·116	1·057	1·023
132	2·010	1·996	1·914	1·834	1·754	1·680	1·605	1·535	1·396	1·290	1·200	1·130	1·069	1·034
133	2·025	2·010	1·929	1·848	1·767	1·694	1·617	1·547	1·408	1·303	1·214	1·140	1·080	1·047
134	2·039	2·025	1·943	1·862	1·780	1·707	1·630	1·560	1·420	1·315	1·226	1·152	1·090	1·058
135	2·055	2·040	1·958	1·876	1·794	1·720	1·644	1·573	1·432	1·326	1·238	1·164	1·101	1·069
136	2·069	2·055	1·974	1·890	1·808	1·734	1·656	1·586	1·445	1·337	1·250	1·175	1·112	1·080
137	2·085	2·070	1·987	1·905	1·821	1·746	1·670	1·600	1·457	1·349	1·261	1·187	1·124	1·094
138	2·098	2·084	2·002	1·919	1·835	1·760	1·682	1·613	1·471	1·360	1·275	1·199	1·135	1·105
139	2·113	2·099	2·018	1·933	1·850	1·774	1·695	1·625	1·485	1·372	1·288	1·213	1·148	1·116
140	2·128	2·114	2·032	1·948	1·864	1·787	1·712	1·639	1·497	1·386	1·300	1·225	1·159	1·127
141	2·143	2·129	2·047	1·962	1·879	1·800	1·725	1·651	1·510	1·399	1·312	1·237	1·170	1·140
142	2·159	2·144	2·062	1·977	1·894	1·815	1·740	1·665	1·523	1·411	1·325	1·249	1·182	1·153
143	2·174	2·162	2·078	1·992	1·912	1·829	1·754	1·679	1·539	1·424	1·337	1·261	1·194	1·165
144	2·189	2·178	2·094	2·010	1·927	1·844	1·769	1·693	1·551	1·436	1·350	1·276	1·208	1·177
145	2·205	2·194	2·110	2·025	1·943	1·859	1·783	1·706	1·565	1·450	1·362	1·290	1·220	1·190
146	2·221	2·210	2·125	2·041	1·959	1·876	1·798	1·720	1·579	1·465	1·375	1·302	1·233	1·204
147	2·239	2·226	2·142	2·056	1·975	1·891	1·812	1·738	1·592	1·480	1·388	1·315	1·245	1·215
148	2·255	2·243	2·159	2·073	1·991	1·907	1·828	1·752	1·606	1·493	1·401	1·327	1·259	1·229
149	2·272	2·260	2·175	2·089	2·007	1·924	1·846	1·768	1·620	1·508	1·414	1·343	1·271	1·243
150	2·290	2·277	2·193	2·105	2·025	1·940	1·862	1·783	1·635	1·521	1·427	1·356	1·284	1·255
151	2·308	2·295	2·210	2·121	2·041	1·955	1·879	1·798	1·649	1·535	1·440	1·370	1·300	1·269
152	2·325	2·313	2·227	2·139	2·059	1·972	1·895	1·813	1·664	1·550	1·454	1·383	1·314	1·282
153	2·344	2·332	2·245	2·155	2·076	1·990	1·910	1·829	1·678	1·565	1·471	1·396	1·326	1·295
154	2·362	2·351	2·262	2·173	2·093	2·006	1·928	1·845	1·695	1·582	1·485	1·410	1·340	1·311
155	2·376	2·370	2·280	2·191	2·111	2·025	1·945	1·861	1·710	1·597	1·498	1·425	1·355	1·324
156	2·402	2·390	2·299	2·210	2·129	2·042	1·961	1·877	1·725	1·613	1·512	1·438	1·371	1·338
157	2·422	2·410	2·316	2·228	2·146	2·064	1·979	1·894	1·740	1·628	1·526	1·452	1·385	1·351
158	2·442	2·430	2·335	2·245	2·164	2·081	1·996	1·910	1·755	1·644	1·540	1·469	1·400	1·365
159	2·464	2·450	2·355	2·265	2·183	2·099	2·014	1·928	1·771	1·660	1·555	1·484	1·415	1·380

TABLE I *(Concluded)*

Extended Distances for PP

Δ°	*Depth h =*													
	Surface	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
160	2·484	2·472	2·374	2·284	2·200	2·117	2·031	1·948	1·786	1·675	1·572	1·498	1·430	1·395
161	2·505	2·493	2·394	2·303	2·219	2·136	2·049	1·965	1·802	1·690	1·586	1·512	1·445	1·408
162	2·527	2·515	2·413	2·322	2·237	2·155	2·066	1·983	1·818	1·709	1·601	1·525	1·460	1·421
163	2·549	2·536	2·433	2·345	2·256	2·173	2·084	2·000	1·836	1·724	1·615	1·540	1·477	1·435
164	2·570	2·557	2·453	2·365	2·275	2·191	2·102	2·018	1·852	1·740	1·630	1·555	1·493	1·449
165	2·592	2·579	2·474	2·388	2·293	2·210	2·120	2·036	1·868	1·755	1·645	1·569	1·506	1·462
166	2·614	2·600	2·494	2·403	2·311	2·229	2·138	2·055	1·884	1·771	1·660	1·584	1·521	1·480
167	2·634	2·620	2·514	2·422	2·330	2·247	2·155	2·073	1·900	1·787	1·674	1·600	1·535	1·492
168	2·655	2·641	2·535	2·441	2·348	2·265	2·175	2·091	1·916	1·802	1·689	1·614	1·548	1·505
169	2·675	2·662	2·555	2·460	2·366	2·283	2·192	2·109	1·932	1·816	1·705	1·627	1·560	1·519
170	2·695	2·682	2·575	2·480	2·384	2·300	2·210	2·125	1·949	1·830	1·720	1·640	1·573	1·533
171	2·715	2·701	2·594	2·498	2·401	2·318	2·225	2·145	1·965	1·845	1·735	1·654	1·585	1·545
172	2·734	2·721	2·615	2·516	2·419	2·334	2·242	2·160	1·981	1·859	1·749	1·666	1·597	1·557
173	2·753	2·740	2·634	2·534	2·435	2·351	2·258	2·175	1·996	1·875	1·763	1·679	1·609	1·569
174	2·771	2·759	2·650	2·551	2·455	2·366	2·276	2·189	2·010	1·888	1·776	1·691	1·622	1·580
175	2·789	2·776	2·667	2·569	2·471	2·382	2·290	2·202	2·024	1·900	1·790	1·703	1·632	1·590
176	2·805	2·793	2·684	2·585	2·486	2·396	2·305	2·215	2·036	1·913	1·803	1·714	1·642	1·600
177	2·820	2·809	2·699	2·600	2·501	2·410	2·318	2·228	2·050	1·924	1·815	1·725	1·651	1·610
178	2·835	2·824	2·714	2·616	2·515	2·424	2·332	2·240	2·061	1·934	1·829	1·735	1·660	1·619
179	2·850	2·839	2·729	2·630	2·529	2·436	2·344	2·250	2·072	1·944	1·840	1·745	1·670	1·626
180	2·865	2·854	2·742	2·645	2·542	2·449	2·355	2·261	2·083	1·954	1·850	1·756	1·678	1·634

TABLE II

Extended Distances for pP

Δ°	Depth *h* =												
	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
0	....	....	....	....	....	....	....	....	....	....	....	....	....
1	....	....	....	....	....	....	....	....	....	....	....	....	....
2	....	....	....	....	....	....	....	....	....	....	....	....	....
3	....	....	....	....	....	....	....	....	....	....	....	....	....
4	−0·031	....	....	....	....	....	....	....	....	....	....	....	....
5	−0·081	....	....	....	....	....	....	....	....	....	....	....	....
6	−0·124	....	....	....	....	....	....	....	....	....	....	....	....
7	−0·155	....	....	....	....	....	....	....	....	....	....	....	....
8	−0·191	....	....	....	....	....	....	....	....	....	....	....	....
9	−0·226	....	....	....	....	....	....	....	....	....	....	....	....
10	−0·258	....	....	....	....	....	....	....	....	....	....	....	....
11	−0·290	−0·119	....	....	....	....	....	....	....	....	....	....	....
12	−0·323	−0·175	....	....	....	....	....	....	....	....	....	....	....
13	−0·359	−0·225	....	....	....	....	....	....	....	....	....	....	....
14	−0·391	−0·270	....	....	....	....	....	....	....	....	....	....	....
15	−0·422	−0·310	....	....	....	....	....	....	....	....	....	....	....
16	−0·453	−0·346	....	....	....	....	....	....	....	....	....	....	....
17	−0·491	−0·384	....	....	....	....	....	....	....	....	....	....	....
18	−0·530	−0·425	....	....	....	....	....	....	....	....	....	....	....
19	−0·581	−0·476	−0·306	....	....	....	....	....	....	....	....	....	....
20	−0·687	−0·555	−0·367	....	....	....	....	....	....	....	....	....	....
21	−0·876	−0·715	−0·455	....	....	....	....	....	....	....	....	....	....
22	−0·970	−0·873	−0·821	....	....	....	....	....	....	....	....	....	....
23	−1·022	−0·937	−0·867	....	....	....	....	....	....	....	....	....	....
24	−1·060	−0·981	−0·905	....	....	....	....	....	....	....	....	....	....
25	−1·094	−1·015	−0·940	−0·853	....	....	....	....	....	....	....	....	....
26	−1·124	−1·045	−0·971	−0·886	....	....	....	−0·067	....	....	....	....	....
27	−1·152	−1·072	−1·000	−0·917	....	....	....	−0·277	....	....	....	....	....
28	−1·180	−1·099	−1·026	−0·941	−0·851	....	....	−0·411	....	....	....	....	....
29	−1·204	−1·125	−1·050	−0·971	−0·882	....	−0·710	−0·489	....	....	....	....	....
30	−1·228	−1·148	−1·074	−0·996	−0·910	....	−0·744	−0·548	....	....	....	....	....
31	−1·249	−1·173	−1·095	−1·018	−0·936	−0·851	−0·775	−0·592	....	....	....	....	....
32	−1·270	−1·194	−1·117	−1·041	−0·960	−0·879	−0·800	−0·626	....	....	....	....	....
33	−1·289	−1·213	−1·136	−1·061	−0·979	−0·900	−0·822	−0·657	−0·500	....	....	....	....
34	−1·308	−1·232	−1·154	−1·079	−0·999	−0·920	−0·841	−0·682	−0·539	....	....	....	....
35	−1·327	−1·249	−1·172	−1·097	−1·017	−0·937	−0·862	−0·705	−0·569	....	....	....	....
36	−1·344	−1·267	−1·190	−1·114	−1·033	−0·955	−0·877	−0·726	−0·596	....	....	....	....
37	−1·360	−1·282	−1·205	−1·129	−1·050	−0·972	−0·892	−0·744	−0·618	−0·475	....	....	....
38	−1·375	−1·298	−1·221	−1·145	−1·066	−0·986	−0·906	−0·761	−0·637	−0·498	....	....	....
39	−1·389	−1·312	−1·235	−1·160	−1·081	−1·000	−0·919	−0·777	−0·656	−0·520	....	....	....

TABLE II *(Continued)*

Extended Distances for pP

Δ°	Depth h =												
	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
40	−1·402	−1·326	−1·249	−1·174	−1·095	−1·015	−0·934	−0·792	−0·671	−0·540	−0·412	....	....
41	−1·415	−1·341	−1·263	−1·189	−1·110	−1·028	−0·946	−0·806	−0·685	−0·558	−0·437	....	....
42	−1·430	−1·354	−1·278	−1·202	−1·124	−1·037	−0·960	−0·820	−0·700	−0·576	−0·460	....	....
43	−1·443	−1·367	−1·291	−1·215	−1·139	−1·058	−0·974	−0·833	−0·711	−0·595	−0·483	....	....
44	−1·457	−1·381	−1·306	−1·229	−1·152	−1·071	−0·987	−0·845	−0·725	−0·610	−0·501	−0·390	....
45	−1·472	−1·394	−1·321	−1·242	−1·166	−1·087	−1·001	−0·859	−0·738	−0·625	−0·520	−0·414	....
46	−1·488	−1·410	−1·336	−1·257	−1·183	−1·102	−1·017	−0·871	−0·751	−0·640	−0·535	−0·434	−0·312
47	−1·505	−1·424	−1·352	−1·273	−1·198	−1·119	−1·032	−0·886	−0·766	−0·656	−0·552	−0·451	−0·351
48	−1·523	−1·441	−1·369	−1·290	−1·215	−1·135	−1·049	−0·900	−0·780	−0·671	−0·568	−0·469	−0·383
49	−1·542	−1·458	−1·387	−1·307	−1·231	−1·152	−1·066	−0·914	−0·796	−0·690	−0·585	−0·485	−0·410
50	−1·562	−1·477	−1·406	−1·325	−1·250	−1·171	−1·085	−0·931	−0·813	−0·707	−0·605	−0·503	−0·432
51	−1·582	−1·497	−1·425	−1·345	−1·268	−1·188	−1·103	−0·948	−0·830	−0·724	−0·623	−0·522	−0·454
52	−1·605	−1·517	−1·445	−1·364	−1·289	−1·209	−1·121	−0·967	−0·850	−0·742	−0·642	−0·541	−0·475
53	−1·627	−1·539	−1·466	−1·385	−1·309	−1·230	−1·142	−0·986	−0·869	−0·760	−0·662	−0·562	−0·495
54	−1·650	−1·562	−1·489	−1·405	−1·331	−1·250	−1·164	−1·007	−0·890	−0·780	−0·682	−0·585	−0·517
55	−1·675	−1·586	−1·510	−1·429	−1·352	−1·272	−1·186	−1·029	−0·911	−0·802	−0·705	−0·607	−0·540
56	−1·699	−1·609	−1·536	−1·451	−1·376	−1·293	−1·209	−1·059	−0·935	−0·825	−0·727	−0·630	−0·565
57	−1·727	−1·634	−1·559	−1·476	−1·399	−1·316	−1·232	−1·076	−0·959	−0·846	−0·752	−0·655	−0·590
58	−1·753	−1·660	−1·583	−1·500	−1·422	−1·339	−1·254	−1·100	−0·980	−0·869	−0·775	−0·683	−0·615
59	−1·780	−1·685	−1·607	−1·524	−1·445	−1·364	−1·279	−1·124	−1·004	−0·894	−0·800	−0·709	−0·645
60	−1·807	−1·708	−1·632	−1·550	−1·471	−1·389	−1·304	−1·146	−1·027	−0·918	−0·825	−0·736	−0·670
61	−1·835	−1·740	−1·657	−1·574	−1·495	−1·411	−1·328	−1·172	−1·054	−0·941	−0·850	−0·765	−0·697
62	−1·864	−1·767	−1·685	−1·601	−1·521	−1·437	−1·354	−1·197	−1·079	−0·965	−0·876	−0·792	−0·725
63	−1·895	−1·797	−1·711	−1·626	−1·545	−1·463	−1·378	−1·224	−1·103	−0·990	−0·902	−0·819	−0·752
64	−1·925	−1·825	−1·738	−1·650	−1·571	−1·486	−1·405	−1·249	−1·127	−1·014	−0·927	−0·847	−0·780
65	−1·955	−1·858	−1·764	−1·678	−1·598	−1·510	−1·428	−1·274	−1·152	−1·039	−0·953	−0·875	−0·807
66	−1·984	−1·882	−1·792	−1·704	−1·623	−1·536	−1·454	−1·296	−1·176	−1·063	−0·978	−0·900	−0·834
67	−2·014	−1·911	−1·819	−1·733	−1·648	−1·560	−1·481	−1·321	−1·200	−1·089	−1·004	−0·925	−1·861
68	−2·043	−1·940	−1·850	−1·759	−1·676	−1·587	−1·505	−1·348	−1·225	−1·112	−1·029	−0·951	−0·888
69	−2·072	−1·970	−1·878	−1·786	−1·705	−1·612	−1·530	−1·373	−1·249	−1·139	−1·054	−0·975	−0·915
70	−2·102	−2·000	−1·907	−1·816	−1·731	−1·638	−1·557	−1·399	−1·274	−1·164	−1·077	−1·002	−0·940
71	−2·132	−2·030	−1·939	−1·844	−1·760	−1·667	−1·586	−1·425	−1·299	−1·191	−1·103	−1·026	−0·969
72	−2·162	−2·059	−1·969	−1·876	−1·790	−1·696	−1·613	−1·451	−1·326	−1·216	−1·130	−1·049	−0·995
73	−2·194	−2·093	−1·998	−1·906	−1·818	−1·723	−1·641	−1·479	−1·349	−1·243	−1·155	−1·074	−1·023
74	−2·230	−2·126	−2·031	−1·940	−1·846	−1·754	−1·671	−1·508	−1·377	−1·271	−1·180	−1·100	−1·050
75	−2·263	−2·159	−2·063	−1·975	−1·876	−1·783	−1·698	−1·534	−1·404	−1·298	−1·205	−1·124	−1·075
76	−2·299	−2·196	−2·098	−2·007	−1·910	−1·815	−1·726	−1·562	−1·431	−1·325	−1·232	−1·150	−1·102
77	−2·336	−2·230	−2·131	−2·041	−1·943	−1·846	−1·755	−1·592	−1·460	−1·352	−1·261	−1·175	−1·132
78	−2·375	−2·273	−2·166	−2·079	−1·979	−1·881	−1·789	−1·620	−1·490	−1·380	−1·289	−1·204	−1·160
79	−2·414	−2·305	−2·206	−2·114	−2·014	−1·918	−1·823	−1·651	−1·522	−1·411	−1·317	−1·233	−1·186

TABLE II *(Concluded)*

Extended Distances for pP

Δ°	*Depth h =*												
	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
80	−2·455	−2·347	−2·242	−2·153	−2·049	−1·951	−1·854	−1·684	−1·552	−1·440	−1·349	−1·263	−1·218
81	−2·497	−2·385	−2·284	−2·190	−2·089	−1·990	−1·890	−1·713	−1·585	−1·471	−1·380	−1·292	−1·245
82	−2·545	−2·425	−2·322	−2·226	−2·125	−2·028	−1·927	−1·749	−1·619	−1·500	−1·410	−1·321	−1·276
83	−2·587	−2·465	−2·360	−2·263	−2·165	−2·066	−1·962	−1·780	−1·650	−1·532	−1·440	−1·355	−1·305
84	−2·630	−2·510	−2·403	−2·300	−2·202	−2·102	−2·000	−1·814	−1·687	−1·564	−1·475	−1·386	−1·338
85	−2·670	−2·551	−2·441	−2·336	−2·239	−2·141	−2·035	−1·849	−1·720	−1·595	−1·506	−1·420	−1·370
86	−2·709	−2·589	−2·480	−2·373	−2·279	−2·177	−2·077	−1·881	−1·755	−1·627	−1·538	−1·454	−1·400
87	−2·747	−2·626	−2·516	−2·408	−2·318	−2·215	−2·115	−1·915	−1·790	−1·656	−1·570	−1·487	−1·430
88	−2·783	−2·664	−2·555	−2·445	−2·351	−2·251	−2·151	−1·951	−1·819	−1·689	−1·600	−1·518	−1·462
89	−2·815	−2·695	−2·588	−2·477	−2·382	−2·282	−2·180	−1·987	−1·850	−1·720	−1·630	−1·548	−1·492
90	−2·845	−2·725	−2·619	−2·507	−2·413	−2·313	−2·208	−2·018	−1·880	−1·751	−1·659	−1·575	−1·521
91	−2·873	−2·753	−2·647	−2·536	−2·439	−2·341	−2·235	−2·044	−1·908	−1·782	−1·684	−1·602	−1·548
92	−2·898	−2·778	−2·673	−2·561	−2·464	−2·364	−2·259	−2·070	−1·932	−1·808	−1·710	−1·626	−1·573
93	−2·920	−2·802	−2·696	−2·583	−2·484	−2·383	−2·279	−2·094	−1·951	−1·834	−1·734	−1·645	−1·595
94	−2·940	−2·823	−2·718	−2·603	−2·501	−2·400	−2·297	−2·114	−1·972	−1·857	−1·753	−1·666	−1·614
95	−2·960	−2·842	−2·735	−2·620	−2·517	−2·415	−2·313	−2·131	−1·990	−1·875	−1·770	−1·684	−1·631
96	−2·975	−2·858	−2·750	−2·635	−2·530	−2·428	−2·329	−2·147	−2·005	−1·891	−1·787	−1·700	−1·645
97	−2·989	−2·874	−2·762	−2·650	−2·541	−2·439	−2·341	−2·160	−2·019	−1·904	−1·800	−1·713	−1·657
98	−3·000	−2·886	−2·774	−2·662	−2·550	−2·449	−2·352	−2·170	−2·031	−1·915	−1·813	−1·725	−1·668
99	−3·010	−2·897	−2·783	−2·673	−2·559	−2·507	−2·361	−2·180	−2·041	−1·925	−1·823	1·737	−1·680
100	−3·017	−2·906	−2·792	−2·682	−2·565	−2·515	−2·370	−2·189	−2·050	−1·933	−1·832	−1·747	−1·690
101	−3·025	−2·913	−2·798	−2·690	−2·571	−2·520	−2·376	−2·196	−2·059	−1·940	−1·840	−1·755	−1·697
102	−3·031	−2·920	−2·805	−2·696	−2·576	−2·525	−2·381	−2·203	−2·065	−1·947	−1·846	−1·763	−1·705
103	−3·036	−2·925	−2·810	−2·701	−2·580	−2·529	−2·385	−2·209	−2·070	−1·953	−1·852	−1·770	−1·710
104	−3·041	−2·929	−2·816	−2·706	−2·583	−2·532	−2·389	−2·215	−2·075	−1·959	−1·858	−1·776	−1·716
105	−3·045	....	....	−2·712	−2·585	−2·535	−2·391	−2·219	−2·080	−1·963	−1·863	−1·783	−1·722
106	....	....	....	....	....	....	....	−2·222	−2·083	−1·967	−1·867	−1·789	−1·728
107	....	....	....	....	....	....	....	....	....	....	−1·872	−1·794	−1·733
108	....	....	....	....	....	....	....	....	....	....	....	−1·800	−1·738

DEPARTMENT OF MINES AND TECHNICAL SURVEYS
DOMINION OBSERVATORIES

PUBLICATIONS

of the

Dominion Observatory

OTTAWA

Vol. XVI No. 12

EDMOND CLOUTIER [illegible]
[illegible]

CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
DOMINION OBSERVATORIES

PUBLICATIONS

OF THE

Dominion Observatory

OTTAWA

VOL. XVI No. 12

DIAMOND DRILLING IN PERMAFROST AT RESOLUTE BAY, NORTHWEST TERRITORIES

BY

PETER C. BREMNER

EDMOND CLOUTIER, C.M.G., O.A., D.S.P.
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
OTTAWA, 1955

TABLE OF CONTENTS

Diamond Drilling in Permafrost at Resolute Bay, Northwest Territories

By

Peter C. Bremner

ABSTRACT

In the summer of 1948 a number of high-resistance ceramic thermometers were placed in shallow holes drilled in the permanently frozen ground at Resolute Bay (latitude 74° 41′ N, longitude 94° 54′ W). During the next year the temperature of the soil was measured daily by Department of Transport officers. The interest engendered by this work led to the suggestion that an attempt be made to drill deep holes and to place temperature-measuring elements at regular intervals to a depth of 1,000 feet. This project was carried out during the four summers of 1950-53, its object being to drill the holes and install thermometers in them. The reading of the thermometers, the determination of temperatures at various levels and the analysis of the results in terms of heat flow from the earth was to be undertaken by the Department of Transport in cooperation with Professor A. D. Misener at the University of Western Ontario.

The program was carried out under great difficulties. Because of transportation problems a relatively light drill was used and because of the low temperature of the ground the drilling water often froze in the hole and seized the rods, necessitating the use of hot water heated to an initial temperature of 190°F. Even this was not sufficient at depths in excess of 600 feet, for the water had cooled almost to the freezing point before it returned to the surface. The work was hampered by caving formations which could not be cased off because of the small size (1½ inches) of the hole being drilled. Due to all these difficulties it was necessary to be content with a maximum depth of 650 feet.

Although the original aim of the work was to drill at least one hole of 1,000 feet, the object of determining the temperature gradient at Resolute Bay was almost as well served by the 10 holes successfully completed from 5 to 650 feet in depth, and equipped with temperature elements at 5-foot intervals to 70 feet, at 10-foot intervals thence to 100 feet and at 50-foot intervals to the maximum of 650 feet.

Cores were taken at all depths to 100 feet and at approximately 50-foot intervals to 650 feet. Some of these cores have been submitted to the Geological Survey of Canada for examination, while the thermal properties of others are being studied at the University of Western Ontario in connection with the general analysis of the project.

INTRODUCTION

During the summer of 1948 the writer travelled to Resolute Bay to investigate the possibility of installing a seismograph station[1] there. In order to determine the depth to bedrock a small diamond drill was required. This, with an operator, was supplied by the Arctic Section of the Defence Research Board. Mr. Andrew Thomson of the Meteorological Division, Federal Department of Transport, suggested that it would be of interest to install soil thermometers in any holes drilled in order to study the temperature and its seasonal variations within the permanently frozen ground and he offered to supply the necessary temperature elements. Seven of these, together with a separate array to measure air temperatures were installed during the summer of 1948, and during the following year temperature observations were made by the staff of the weather station.

From this small beginning grew the program described in this paper. The initial proposal, first advanced by Mr. Thomson, was that 2 holes be drilled to depths of 100 feet and 1,000 feet respectively, and that multi-element temperature cables be installed in each. By comparing the temperature gradient extrapolated from the 100-foot hole

---

[1] Bremner, P. C., "The Dominion Observatory Seismic Station at Resolute Bay, Northwest Territories", *Publications of the Dominion Observatory*, Vol. XVI, No. 2, 1952.

with that actually observed at greater depths, it would be possible to ascertain whether the observed temperature gradient was a consequence of present day climatic conditions or whether there were effects remaining from a previous epoch, and to study the general question of heat loss from the earth's crust under Arctic conditions. The Dominion Observatory undertook to supply the drill and all necessary auxiliary equipment. The Meteorological Division of the Department of Transport, with some financial assistance from the United States Weather Bureau, hired the drilling personnel and arranged for their board and lodging at Resolute. The United States Weather Bureau also supplied the two multi-element temperature cables and numerous other items of equipment, besides arranging for the transportation of the original equipment to Resolute Bay. Subsequent delivery of equipment, including emergency transportation of supplies, was undertaken by the Air Transport Command, Royal Canadian Air Force. The Canadian Longyear Company supplied the drilling equipment and offered advice and special service far beyond their commercial obligation.

The program began during the summer of 1950 under the supervision of the writer, who was at Resolute Bay to install the seismograph station. What had been planned as a one-year program actually continued throughout the four summers of 1950-53 due to the extreme difficulty experienced in drilling in the permafrost. It was continued on the same co-operative basis as outlined above, with additional financial assistance during the final season through the Associate Committee on Soil and Snow Mechanics of the National Research Council. The original program had to be modified repeatedly because of the difficulties encountered, so that instead of the 2 holes originally proposed, 21 holes were drilled, the maximum depth at which a temperature measuring element was placed being 650 feet.

Part of the cores obtained in the course of the project were supplied to the Geological Survey of Canada and others were sent to Professor A. D. Misener of the Department of Physics, University of Western Ontario. Professor Misener has undertaken to report on the thermal properties of these cores and on the interpretation of the temperatures measured in the holes.

The present paper is limited to a description of the actual drilling, an analysis of the difficulties encountered and recommendations based on that analysis. It is hoped that the experience gained in drilling in permafrost will be of assistance to others who may have similar drilling problems.

DESCRIPTION OF EQUIPMENT

DRILLING EQUIPMENT

Elementary Description

For the benefit of those not acquainted with diamond drilling techniques, a diagram of a drill is reproduced in Figure 1. The complete drilling rig consists of the drill with a tripod, bearing a sheave at its apex, mounted above it. A wire rope passes from the draw works of the drill up through the sheave in the tripod and may be used to raise or lower the drill rods.

The drill itself consists of four essential parts, an engine to supply power, a transmission to carry this power to the drilling head, the draw works already mentioned and the drilling head. The drilling head may be rotated, so that the hole may be drilled at any desired angle. The drill pipe, as indicated in the figure by a broken line, passes through the drill head, entering through the feed screw at the top and emerging through the chuck at the bottom. In lowering rods into the hole they are let down by means of the draw works until the bottom of the hole is reached; then a set screw in the chuck is tightened and the rotation of the chuck is so transmitted to the rods. The feed screw can be advanced as the hole is drilled.

The drill rod, which is hollow, terminates at its lower end in a bit—which may be either a core bit or a solid bit of one of several varieties—and at its upper end in a water swivel. Water is pumped through the swivel, down the drill rod, and out through holes in the bit, where it carries away the cuttings and forces them to the surface on the outside of the drill pipe. In discussing the equipment assembled for the project, the drilling rig, the drill rods, the pumping and the water heating equipment are described, the last named being of prime importance because of the freezing action of the permafrost.

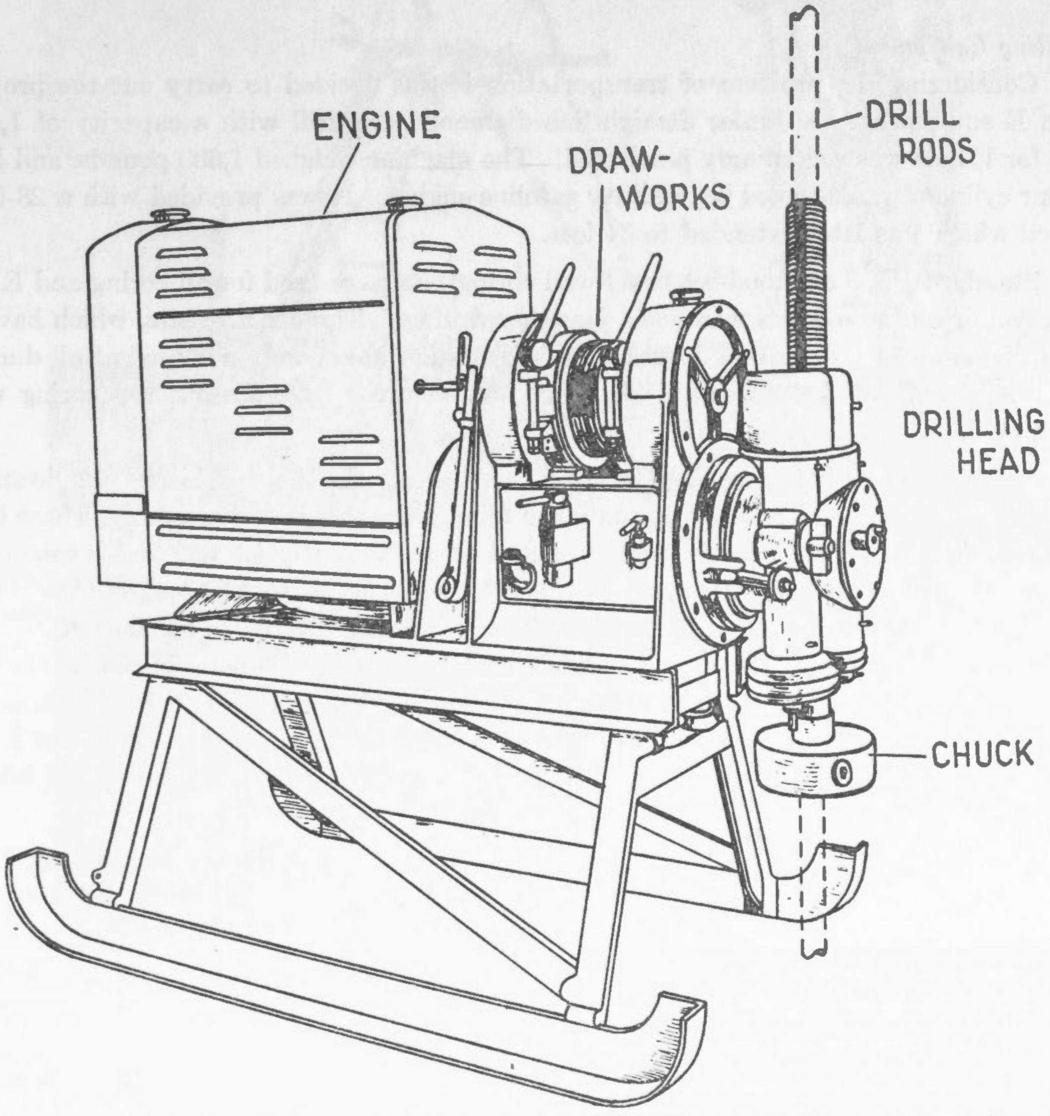


Figure 1.—Diamond core drill, screw feed advance. Rated at 1,000 feet of $1\frac{7}{8}''$ hole recovering $1\frac{5}{16}''$ core.

Equipment Designations

It is convenient in the following description to refer to equipment dimensions in the standard nomenclature. This nomenclature may be defined in terms of four casing sizes, designed to fit one inside the other. The smallest casing, designated EX, has an inside diameter of $1\frac{1}{2}$ inches, an outside diameter of $1\frac{13}{16}$ inches. The next size, AX, has an inside diameter of $1\frac{29}{32}$ inches, and an outside diameter of $2\frac{1}{4}$ inches. There are two larger sizes, BX and NX, with which we are not concerned. Other equipment is designated in terms of the casing through which it will pass. For example, an EX bit will pass through EX casing, an AX reaming shell will pass through AX casing.

The above designations are those of United States manufacturers. Canadian firms use the same casing sizes, so that Canadian tools will pass through the related casing size. For most other equipment Canadian specifications differ but slightly from those of United States manufacturers, but are distinguished by the addition of the letter T, as AXT and EXT. An EXT bit, either coring or bull-nosed, has an outside diameter of 1·460 inches.

Drilling Equipment

Considering the problem of transportation it was decided to carry out the project with E equipment. A Junior Straightline diamond core drill with a capacity of 1,000 feet for E hole was accordingly purchased. The machine weighed 1,600 pounds, and had a four-cylinder water-cooled heavy-duty gasoline engine. It was provided with a 28-foot tripod which was later extended to 34 feet.

Standard EXT diamond-set bevel-wall coring bits were used for all coring and EXT concave, or bull-nosed bits were used for other drilling. The concave bits, which have a solid diamond-set face except for the water-circulation holes, were not used at all during the first season, all holes being drilled for core. During later seasons less coring was attempted.

In taking cores it is necessary to use a core-barrel. As the core bit travels down, a cylindrical piece of rock passes into the inner tube of the core barrel assembly, where it is held from falling out by a small spring, called a core lifter. Rigid type, double tube core barrels of various lengths were used in the project. The circulating water flows down between the inner and outer tubes of these barrels and is delivered to the face of the bit through small holes at the lower end of the inner tube. As the diameter of the core barrel ($1\frac{1}{16}$ inches) is slightly greater than the diameter of the drill rods ($1\frac{5}{16}$ inches) it tends to restrict the return flow of water. Special core barrels were constructed, three feet long, with a spiral water groove cut along their length and these were used during the latter part of the project.

The initial pumping equipment purchased consisted of 2 duplex pumps, rated at 1,000 gals/hr., and driven by a 4-cycle $6\frac{1}{2}$ h.p. gasoline engine. It was intended that one of these would be used in drilling, the other to pump water to the drill site from a fresh-water lake some distance away. The pump units were not capable of delivering sufficient pressure when deep drilling was being done and higher capacity pumps were borrowed from the weather station and incorporated into the water system. The most important of these were 2 three-stage centrifugal pumps with a rated capacity of 200 gals/min. through a 300-foot head.

Figure 2.—Drill set-up showing tripod and two coil water heaters.

The water-heating equipment used during the first summer proved completely inadequate for the purpose. It consisted of a coil made from many lineal feet of copper tubing. This coil was set in an insulated jacket and mounted about 15 inches above a combustion chamber where it was heated by the hot exhaust gases. Fuel oil was delivered into the fire pot, the quantity being controlled by a carburetor similar to those used on commercial space heaters. The unit was rated to raise 300 gallons of water per hour through 50°F.

When the unit was new it delivered hot water at about the specified rate but after burning for half a day the temperature of the output dropped considerably. The decrease in efficiency was due to incomplete combustion of the fuel oil, which resulted in a layer of carbon about $\frac{1}{8}$ inch thick being deposited on the coil. All efforts to obtain complete combustion by increasing the draft and by preheating the fuel oil met with little success. The efficiency of the heater was increased by reducing the quantity of oil entering the fire-box but the overall heating effect was decreased because of the smaller fire. A better supply of hot water might have been forthcoming if it had been feasible to clean the coil while the fire was burning, but to reach the coil the stove had to be shut down and dismantled. Even after the carbon had been removed the coil was covered again within three hours.

The arrangement ultimately arrived at for heating water proved capable of raising 350 gals./hr. from 40°F up to 190°F. It consisted of 2 units working in series. The first unit was a coil heater, weighing about 350 pounds, constructed from a commercial type water-heater coil mounted in a 45-gallon drum lined with fire brick. The unit was fired with fuel oil and a strong draft was induced by a 16-foot smoke stack. The coil through which the water circulated was at the top of the combustion chamber where the flames could burn off any excess carbon which might deposit on the tubing. In addition, the draft stack could be removed readily to allow the operator to clean the coil with a wire brush. The second unit consisted of an oil-fired marine type boiler with an electric burner and thermostat controls. It weighed one ton, had dimensions 75 inches x 43$\frac{1}{4}$ inches x 34$\frac{1}{2}$ inches, and was rated to raise 410 gals./hr. through 100°F. Its performance was satisfactory, but considering its size and weight a series of the simpler heaters might have been more satisfactory.

Because of supply difficulties, troubles were anticipated as much as possible and duplicate parts and fishing tools of various sorts were ordered. The use of these is mentioned from time to time in another section.

TEMPERATURE MEASURING EQUIPMENT

The temperature-measuring equipment supplied during the life of the project is listed in Table I, which also indicates the ultimate use made of the several cables. The hole numbers referred to are described in Table III in a later section.

TABLE I

Temperature Measuring Elements and Cables Supplied for the Project

Type of Element or Cable and Year Supplied	Element or Cable Designation	Supplier	Ultimate Use See Table III
1948			
Ceramic Resistance Thermometers	Elements No. 1-13	D. of T.*	See Table II
1950			
100 foot Multi-Element *(Temperature measuring elements at 5 foot intervals from 0 feet to 70 feet and at 80 feet, 90 feet, 100 feet)*	No. 146	U.S.W.B.†	Hole No. 1
1,000 foot Multi-Element *(Temperature measuring elements at 50 foot intervals from 150 feet to 1,000 feet)*	No. 147	U.S.W.B.	Hole No. 20
Ceramic Resistance Thermometers	No. 1	D. of T.	Hole No. 5
	No. 2	"	Hole No. 2
	No. 3	"	Hole No. 4
	No. 4	"	Hole No. 3
	No. 5	"	Surface
	No. 6	"	Hole No. 6
1951			
300 foot Single Element	No. 170	U.S.W.B.	Hole No. 9
500 foot Single Element	No. 171	"	Hole No. 14
1,000 foot Single Element		"	Accidentally destroyed while in storage
1953			
750 foot Single Element		U.S.W.B.	Hole No. 21

* Meteorological Division, Department of Transport, Canada.

† United States Weather Bureau.

ACCOUNT OF THE DRILLING OPERATIONS

At the time of the writer's first visit to Resolute Bay in the summer of 1948, the Meteorological Division, Department of Transport, supplied 13 high-resistance ceramic thermometers, numbered 1 to 13. In order to have a complete record in one place the disposal of these elements is listed in Table II, below, although these preliminary studies were not, properly speaking, part of the program described in this paper.

TABLE II

Temperature-Measuring Elements Installed in 1948

Element Number	Disposal
2	Mounted in a radiation shield on the radio antenna. Height 22 m.
3	Mounted in a radiation shield on the radio antenna. Height 11 m.
4	Mounted in a radiation shield on the radio antenna. Height 2 m.
5	Mounted in screen. Screen dry.
6	Mounted in screen. Screen wet.
7	Placed in disturbed soil in pit. Depth 42 cm.
8	Placed in disturbed soil in pit. Depth 85 cm.
9	At surface.
10	In drilled, uncased, hole. Depth 10 cm.
12	In drilled, uncased, hole. Depth 20 cm.
11	In drilled hole, cased with rubber garden hose. Depth 45 cm.
1	In drilled hole, cased with rubber garden hose. Depth 100 cm.
13	In drilled hole, cased with rubber garden hose. Depth 150 cm.

The sections that follow trace the progress of the drilling program throughout the four summers operations. This account seems necessary in order that the drilling techniques ultimately arrived at will be understood and their necessity appreciated. The information is summarized in Table III.

TABLE III

Hole No.	Year Drilled	Depth of Hole (feet)	Depth of Temperature Element (feet)	Type and Designation of Temperature Element	Core Recovery Range (feet)	Remarks
1	1950	103	100	100-feet Multi-Element	5—103	Surface casing, from 1 foot to 7 feet, could not be removed.
2		23	21½	Ceramic No. 2	6½— 23	
3		52	50½	Ceramic No. 4	6½— 50	
4		30	28	Ceramic No. 3	6½— 30	
5		11	10	Ceramic No. 1	6½— 11	
6		6	5	Ceramic No. 6	—	
7		130	—		7—130	Drill rods seized in hole due to freezing. Recovered 70 feet.
8		188			20—188	Hole abandoned at 188 feet because of close of season. Filled with pure anti-freeze and capped.
	1951				188—190	Hole was re-entered at start of 1951 season but rods became frozen in the hole. 60 feet of rods and 10 foot core barrel lost.
9		300	300	300-foot Single Element		
10		385				Drill rod seized when pump failed. 320 feet of rods and 10 foot core barrel lost.

TABLE III (*Concluded*)

Hole No.	Year Drilled	Depth of Hole (feet)	Depth of Temperature Element (feet)	Type and Designation of Temperature Element	Core Recovery Range (feet)	Remarks
11	1951	355				Hole abandoned because of cave. No loss of equipment.
12		385				Rods stuck, apparently due to sludge accumulated in the hole. 340 feet of rods and core bit lost.
13		300				Hole lost at 300 feet. 10 foot core barrel left in hole but all rod recovered.
14		450	450	500-foot Single Element		So much drill rod had been lost during the season that it was necessary to install element at 450 feet rather than the 500 feet proposed.
15	1952	682				Drill rods stuck by frost action. 300 feet of rods and 2 foot core barrel left in hole. Attempts to drill over rods with casing unsuccessful.
16		512				Drill rods stuck by frost action. 110 feet of rods lost. Attempt to free rods by drilling over them with casing discontinued when expansion of casing joints increased pump pressure dangerously.
17		662				Hole reamed to AXT whenever increasing pump pressure indicated poor circulation. Drill rods stuck by caving rock at 660 feet. Core barrel and 10 feet of rods lost. An additional 600 feet of rods were lost in attempting to fish core barrel.
18		740			5 ft.-10 ft. cores, at 50 ft. intervals, down to 600 feet.	Reaming technique continued. Failure of thread on rods resulted in loss of 265 feet of rods.
	1953					An attempt was made to fish these rods at the beginning of the 1953 season by washing over them with casing with left-hand thread. Efforts were defeated by repeated cave at a depth of about 200 feet.
19		687				Hole reamed at same time as it was drilled by mounting reamer above bit. Pressure built up at depth of 687 feet and in attempting to free rods a rod coupling was sheared, leaving 527 feet of rod and the reaming bit in the hole. 230 feet of rods were recovered by fishing.
20		675	650	Multi-Element No. 147		Same technique as Hole 19. Rods jammed at 675 feet and rod coupling sheared leaving 180 feet of rods in the hole. All but 20 feet of these were fished out and temperature cable was lowered to depth of 650 feet.
21		300	115			Hole drilled at angle of 45° under ocean. Depths indicated were measured along hole, not vertically.

Summer of 1950

Description of Work

The diamond drill and its accessories were sent to Resolute Bay by sea, arriving on August 20, 1950. By this time the seismograph station had been installed and the writer was free to devote most of his time to the drilling program.

During the next week a drill-shelter, 12 feet long, 9 feet wide, and 8 feet high, made from dunnage off the beach, was erected on a sled. The wooden shelter, which was later covered with tar paper, was designed to accommodate the drill, one water heater, and an oil-fired space heater. A 28-foot steel pipe tripod was set up for hoisting and lowering the rods and the remaining equipment was made ready for immediate operation. The 2 new water pumps and the new drill engine were carefully run in to avoid delay when the drillers arrived.

The two diamond drill operators arrived at Resolute on August 30. Work began at once on the problem of supplying water for use at the drill. As a continuous supply of hot water was required at a rate of 400 gallons per hour it was decided to pump the water to the drill from the fresh water lake 1,500 feet west of the station. A 1,500-foot line, made up of 25-foot lengths of flexible steel hose, was laid from the drill to the water pump, which was housed in a wooden shelter at the lake. This system delivered plenty of water but the day after it was started the weather turned cold and the water quickly froze in the steel hose.

To continue with this system meant either heating the water before it passed through the line or, alternately, heating the line. An attempt was made to do the latter by using an arc welder as the power supply for an electrical heater in which the steel pipe represented the heating coil. Though this idea proved quite successful when applied to individual lengths it could not be used over the whole line since rubber gaskets in the hose couplings insulated consecutive lengths from each other. It was decided to put a 1,000-gallon tank on a sled by the drill and keep the machine supplied with water hauled from the lake.

This system was satisfactory if the pump in the station water-wagon did not break down. The water was sucked from the 1,000-gallon tank by one of the two pumps located at the drill, and forced through the coil heater into a 50-gallon reservoir also located inside the drill shelter. The second pump took hot water from the reservoir and pushed it down the hole. A system of valves and lines enabled the operator to circulate water from the tank through the coil heater and back into the cold water reservoir if the drilling was stopped and the 50-gallon hot water tank was full.

With the problem of water supply solved, final adjustments were made at the drill set-up before beginning the first hole, which was to accommodate the 100-foot cable. On September 3, the hole was started. A 2½-inch pipe was driven down to bedrock, about 5½ feet below the surface, by thawing the ground with water and using a 350-lb. drive block. The overburden was frozen gravel and the rate of penetration through the last 18 inches was extremely slow due to the rock-like hardness of the permafrost Flush joint EX casing was drilled down 7 feet, and the drilling was commenced.

At the end of the second day the hole was down 68 feet. It was then pumped full of fuel oil and left over-night. The following morning the hole was frozen solidly to within 14 feet of the surface. Either the oil had not reached the bottom of the hole or the water had percolated down, displacing the lighter fuel oil. In the next shift the ice was re-drilled and the hole was continued to 103 feet, the extra 3 feet being allowed for ice which formed while the rods were being hoisted.

The hole was then deep enough to receive the 100-foot multi-element cable, but there was so much cave at regular intervals that cement was poured in to prevent further restrictions from forming. Though the cement mixture was very fluid and free of any lumps it only hardened in the first 15 to 20 feet of the hole. Next day the cement and ice were drilled out and the rods raised and lowered until the restrictions were cleared. After each run to clear the hole, 3 or 4 feet of new ice had to be re-drilled. The reel containing the temperature cable was mounted inside the shelter so that the unit could be quickly lowered. Before inserting the thermometer a brass weight was lowered on a strong line to determine whether or not the passage was open. After two trials with the weight, separated by delays in which the new ice was re-drilled, the cable was lowered.

Since the temperature elements were closely spaced from the surface down, it was most desirable to remove the 7 feet of casing. However, all attempts to do this failed. A steam jet thawed out the permafrost to bedrock and warm water even circulated out of the top of the rod. After this, pipe wrenches and even the force of the tractor fork-lift were applied but the casing had apparently become securely cemented in the rock. It was therefore cut off about 12 inches below the ground surface and the gravel carefully replaced to make the material over the elements as much like the undisturbed ground as possible. The 200-foot lead-in cable was encased in a wooden conduit which led from the drill hole into the administration building. Observations were begun at once to record the "settling" of the drill hole.

A similar drilling procedure was used to place the ceramic elements supplied by the Meteorological Division at depths of 0, 5, 10, 21½, 28, and 51½ feet. However, for these shallow holes the flush joint casing was successfully removed as follows: while the hole was still "warm" from the drilling, a pipe wrench was clamped on the casing and tied to a heavy rope leading over the tripod sheave wheel to the hoist drum. A second pipe wrench was used to rotate the casing while the hoist applied the necessary tension to pull the casing up over the thermometer cable. These elements were installed at the rate of one a day, and observations were started without delay.

The drilling arrangement was slightly altered before making a first attempt to drill the 1,000-foot hole. The tripod legs were increased from 28 to 34 feet, permitting the rods to be pulled and broken in 20-foot sections rather than 10 as had been done in the 100-foot hole. The 1,000-gallon tank and its associated pump were enclosed in a canvas shelter and all other equipment was checked before continuing the operation.

Following the usual procedure, a section of 2½-inch pipe was driven down 7 feet to bed rock with the aid of warm water and the 350-lb. driving hammer. The casing was then drilled down 20 feet to reduce the possibility of cave caused by the shattered condition of the surface layers. At the end of the shift the hole was down 40 feet, fuel oil was poured down the rods as they were raised and decoupled one at a time. Between shifts water percolated into the hole and by morning the cavity was frozen. The ice was drilled out and boring was continued to a depth of 90 feet. This time the hole was filled with a solution of anti-freeze and water in the ratio of 8 quarts of anti-freeze to 12 quarts of water.

This solution proved much more successful and at the beginning of the next shift the first 72 feet of the hole were clear, while the bottom 18 feet were slush. The rods were lowered, without hot water being circulated, as far as they would go. The core barrel became clogged with ice, making it necessary to hoist the rods at once. No difficulty was experienced in removing the rods and after the core barrel was changed they were let down a second time, being stopped every 30 feet or so to test whether or not water could be circulated. Drilling was then continued to a depth of 130 feet with no complications. Ice was now starting to form rapidly at the bottom of the hole during the time when the rods were being hoisted and the core barrels interchanged, but as yet the rods showed no tendency to freeze to the walls of the hole. The temperature of the drilling water was probably around 75°-85°F.

At 130 feet the hole was again filled with anti-freeze which, this time, kept it completely free of ice. The following morning a T-joint was put on the top of the casing to facilitate the recovery of the solution, as the supply of anti-freeze was limited. The rods were lowered to the bottom and the water swivel attached. Water circulation was not possible. The hoisting plug was quickly replaced, but unlike the previous occasion, the rods rose a foot or two and then became seized in the hole.

By the time the first three or four 10-foot lengths of rod had been removed with the rod spear, the rest of the string was frozen solidly in the hole and the spear was of no further use. It was decided to try to free the rods by drilling down over them with flush joint casing. This yielded good results until at 70 feet the joints of the casing began to spread and this procedure had to be abandoned. Some 60 feet of drill rod, a core barrel, and the diamond bit were left in the ground.

The second attempt to drill a 1,000-foot hole was abandoned when it became evident that deeper bore holes could be completed only if the drilling was continued day and night until the required depth was obtained. Filling the hole with anti-freeze and allowing it to stand overnight had resulted in delays and near losses of equipment, which could not be tolerated. As in the earlier drilling no severe difficulties were encountered in the first 100 feet or so. However, considerable time was wasted in drilling ice which formed each time the rods were hoisted to change a core barrel. At depths over 150 feet as much as 40 or 50 feet of hard ice was often drilled. This would take several hours as the drilling head was not equipped with high speed reaming gears which would have been ideal for boring ice. Had extremely hot water been available the rods could have been lowered more quickly without fear of freezing them in the ground.

Another serious delay occurred at the beginning of each shift, when the rods were let down after the hole had cooled for about 12 hours. As soon as the anti-freeze solution was forced out, the danger of frost seizing the rods was great. On several occasions the drilling tools were nearly frozen in the ground. Apparently the tendency of the rods to freeze is caused by the presence of ice crystals on the walls of the drill hole. When the rods are lowered after a small delay the core barrel pushes the frost ahead of it like a plough until ice blocks the circulating channel between the inside of the rod and the outside of the core tube. Finally, the quantity of slush ahead of the rods may become so great and tightly packed as to prevent the string from further descent. It is impossible to circulate water, consequently the rods must be hoisted. As the upward journey starts the remaining frost on the wall begins to gather around the guide ring on the core barrel, and perhaps in the narrow space between the core barrel and the wall of the hole. Quickly the friction increases, ice wedges against the core barrel, and the string seizes in the hole.

To combat this effect the technique was developed of lowering the rods through the drill head rather than simply lowering them from the tripod sheave and of attaching the water swivel and circulating hot water for thirty seconds or so after each rod was attached. However, this procedure was time-consuming and as much as a half of each day's working time had to be devoted to opening up the hole already drilled. It was decided to attempt to circulate hot water through the drill hole all night, but shortage of manpower made this unfeasible. Therefore the hole, which was 188 feet deep, was filled with pure anti-freeze and stopped with a metal cap.

Little difficulty was encountered in logging core for the 103-foot and 188-foot holes. Special boxes were provided for storing the samples, which were made up entirely of fossiliferous limestone. Near the surface only small pieces of core were recovered, but after reaching a depth of 100 feet, long unbroken pieces were obtained, indicating that the rock was more solid.

Analysis of the Summer's Difficulties

The measurement of soil temperatures made as a result of the first season's work revealed the cause of many of the drilling complications and suggested modifications of technique. The first 50 feet of frozen ground exhibit seasonal variations with temperature, but at a depth of 50 feet an unvarying temperature of $-13°\cdot 5$ C. ($7°\cdot 7$ F.) is found. This is believed to be the coldest ground temperature on record.

Because of these extreme temperatures a supply of more and hotter water was recognized as a necessity and it was also apparent that drilling should proceed on a 24-hour basis so that the hole would have no opportunity to cool off. To reduce the amount of time required in removing the rods it was decided that less core-drilling be attempted and that the effort be directed principally towards making hole rather than obtaining core.

Summer of 1951

Description of the Summer's Work

The difficulties experienced during the 1950 season suggested that it might not be practical to drill a single 1,000-foot hole and to insert the multi-element cable in it. The program was accordingly modified. It was agreed that efforts should be directed towards drilling holes to depths of 300 feet, 500 feet and 1,000 feet and to insert single-element cables in them. In this way something could be accomplished even if the 1,000-foot hole could not be completed.

The recommendation, based on 1950 experience, of 24-hour operation was met by sending sufficient drilling personnel to operate two 12-hour shifts. It had been recommended that a third man be available on each crew to service the pumps and heating equipment but this could not be arranged. The writer again supervised the project and was responsible for installing the temperature cable.

FIGURE 3.—Drill set-up showing location of the three water pumps, water heaters and the diamond drill.

The drilling crew arrived at Resolute on July 7. The new heating equipment, consisting of the coil heater and marine boiler already described were set up in an open line system between the 1,000-gallon cold water reservoir and the 50-gallon reservoir for hot water. This system reduced the danger of bursting hose lines and of injury to the drillers and did not require the use of pressurized hoses except for the swivel hoses leading from the pressure pumps to the drill rods. For depths up to 150 feet, only the marine boiler was used as water temperatures around 140° were sufficient to drive the frost back from the walls of the hole. At greater depths, or if delays were frequent, both heaters were used in series to produce water between 150° and 190°F.

The circulating system used during the second season proved very satisfactory and was not subsequently modified. The details are shown in Figure 4. It included a spare pump to be switched into the line if either the pressure or supply pump failed. The pressure pumps must be built to withstand the continual hot water and great stresses on the plungers. Water pressures at the face of the bit varied between 175 and 200 lbs. per square inch; in holes up to depths of 450 feet the rate of water flow was finally raised to between 300 and 450 gallons per hour.

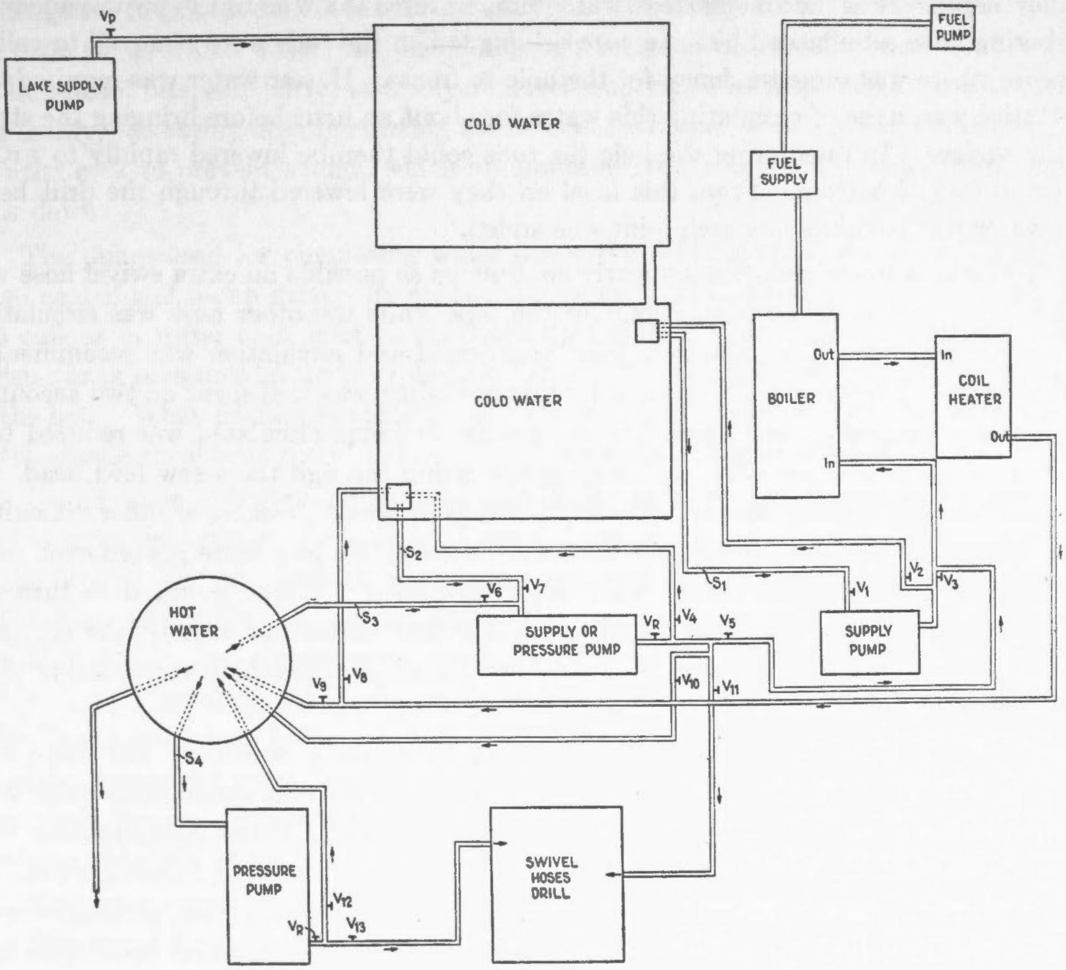


FIGURE 4.—Circulatory system for heating water and providing continuous flow through the drill hole.

A careful study of Figure 4 shows that each of the fifteen valves included play an important part in ensuring rapid and close control over the supply of hot water to the drill. Valves V_2 and V_3 on the output side of the supply pump together regulate the rate of flow through the heaters, ensuring that only the required volume of water is heated. When the rods are to be hoisted, and hot water is not required for several minutes, valves V_8, V_9 return the hot water to the 1,000-gallon reservoir, conserving water and heat. A similar system is used at the pressure pumps to regulate the pressure and rate of flow down the hole, and to re-claim the hot water when there is no flow through the rods. A third system of valves enables the spare pump to be used either for pressure or supply. On the intake side of this pump are two suctions, one for cold water the other for hot. On the output side, two separate sets of valves channel water through the heaters or through the swivel hose.

After a satisfactory heating unit and an efficient circulating system had been assembled drilling was commenced on a basis of 24-hour operation during the drilling of each hole. Although the 188 foot hole, which was left full of anti-freeze in October 1950 was lost, along with considerable drill rod, because the hole was re-entered too quickly, it soon became evident that the improved technique had eliminated permafrost complications at shallow depths. For the first 200 feet, water temperatures as low as 130°F. proved adequate for boring with a bullnosed bit. In core drilling, when the rods were removed to collect the core, there was some tendency for the hole to freeze. Hotter water was required and a practice was made of circulating this water for about an hour before bringing the string to the surface. In re-entering the hole the rods could then be lowered rapidly to within 50 or 60 feet of bottom. From this level on they were lowered through the drill head, and water was circulated as each joint was added.

To make water circulation as nearly continuous as possible an extra swivel hose was used. This was made up to one joint of the pipe while the other hose was circulating through the string. Then the new joint was added and circulation was recommenced immediately. The extra time required by this procedure was well spent on two accounts. Firstly, the interval during which hot water was not being circulated was reduced to a fraction of a minute; secondly, by lowering the string through the screw feed head, the machine could be used at once to withdraw the rods if signs of freezing or other difficulties were apparent. When complications were encountered, this procedure proved even more successful if the rods were turned with wrenches during the time required to turn the drill chuck down over the rods to permit another lift. Attempts to hoist the string as soon as difficulties were indicated, without first reversing the machine and rotating them back several feet, often met with failure.

About 48 hours of drilling were required to reach a depth of 300 feet with the bullnosed bit. After circulating hot water for 3 hours the first temperature cable with a single element was lowered and readings were commenced. Minor complications were encountered but none of these could be attributed to the permanently frozen ground.

Attempts to reach a depth of 500 feet were less successful and serious difficulties were encountered at depths around 350 feet. On four consecutive occasions holes were lost along with a total of 700 feet of drill rod at depths of 385 feet, 355 feet, 385 feet, and 300 feet respectively. For each of these runs the water temperature was never below, and was usually well above 140°F., showing that frost was not primarily, if at all, responsible for these delays.

Observations of rates of cooling already made in a shallower hole tended to support the opinion that frost was not to blame for the sudden and unpredictable loss of bore holes and equipment. Two other causes seemed probable, one that all the sludge was not being washed out of the hole, the other that the bit was mudding in natural sand deposits in the rock. Whatever the sources of trouble, it was manifested by an abrupt reduction in the amount of water passing through the rods, combined with a strong tendency for the rods to stick fast in the drill hole. In one instance the rods were recovered when these complications arose by applying the procedure described above; that is, the rods were rotated and raised by means of the swivel head until they were 3 or 4 feet off bottom. During the time the swivel head was being turned down the rods were held off bottom with the lifting bail and kept moving with pipe wrenches. After raising the string several feet, the hoisting equipment was used in the customary manner.

As a result of these additional complications three aspects of the operation were investigated to improve methods for removing all the sludge from the bore hole. First, the pressure at which water was forced through the rods was greatly increased; second, the bull-nosed bits, core barrel assembly, and rod couplings were inspected for constrictions; and finally, the casing used in starting the hole was wrapped with canvas and driven well into the rock to prevent sludge, which accumulated at the top of the hole, from seeping back down.

The pump used for circulating water down the drill rods was replaced by a three-stage centrifugal pump driven by an 80 h.p. engine. This machine could easily deliver 400 gallons of water each hour at pressures up to 300 lbs. per square inch. It did not register back pressures on the pumping mechanism, and thus did not indicate constrictions in the hole. When drilling at these pressures a flexible steel swivel hose was used in place of the standard rubber type which frequently burst under the additional strain.

Examination of bull-nosed bits, reaming shells, and core barrel back-end connections offered some opportunity for increasing the volume of water being circulated. The hole in the face of the bull-nosed bit was made larger and a second smaller hole was made in the wall of the bit near the cutting face. The water grooves in the bit were made considerably deeper and aligned with water grooves on the reaming shell. This system provided an alternative water passage if the face of the bit mudded, for then water could pass out the small hole in the side wall of the bit and keep hot water moving through the ground. Additional water grooves were cut in the reaming shells and the original groover was made deeper. The back-end connections for the core barrels were inspected for spurious materials which might prevent circulation but were otherwise unchanged.

The most important discovery arising from the inspection of the drilling apparatus was that few of the rod couplings were properly machined before leaving the manufacturer. The water passage in the standard E rod coupling measures 0·441 inches, inside diameter.

Those supplied in this case averaged only 0·370 inches. As there are 10 end couplings in each 100 feet of drill rod the reduced size of the water passage necessitates a considerable increase in water pressure to maintain a given rate of flow. The rod couplings were drilled out to have the correct inside diameter.

Efforts to set the casing firmly in the rock were only partly successful as the continual rod vibration soon worked the casing loose in the soft limestone. So long as the casing was tight, the return water appeared on surface, where it was passed through a sludge box enabling the solid material to be collected and removed from the top of the hole. However, when the casing worked loose an alternative path to surface was provided between the outside of the casing and the wall of the drill hole. Sludge collected at the top of the casing for it was filtered out as the water passed off through the gravel. Materials accumulating in this fashion might well seep back into the hole and cause complications at greater depths. A possible remedy for this is mentioned below.

Following these alterations another attempt was made to reach 500 feet. Water temperatures were closely watched and kept above 150°F. Checks on the rate of circulation revealed that, with water pressures kept at 200 lbs. per square inch, water was being circulated at close to 400 gallons an hour as compared with 150 gallons an hour for the previous shallow holes. Table IV relates water pressure, water temperature, and rate of circulation with depth for this hole. The increased circulation seemed to overcome all earlier difficulties and boring was continued to 450 feet, at which time a shortage of drill

TABLE IV

Depth of Bore Hole	Water Pressure	Rate of Circulation	Temp. of Water Entering Drill Rods	Temp. of Water Returning from Hole
feet	p.s.i.	g.p.h.	°F.	°F.
92	100	235	140	115
105	100	232	138	116
150	130	232	152	117
180	135	232	152	120
200	150	250	151	118
215	150	250	148	117
286	170	420	155	130
312	170	430	164	148
358	175	390	173	136
368	170	375	167	143
378	190	375	167	152
390	170	315	176	150
398	200	420	190	150
405	190	420	185	148
414	190	375	172	148
420	190	375	176	156
430	200	375	183	164
440	190	390	173	153
450	190	370	174	154

rods made it impossible to drill deeper. No complications were encountered and in all probability greater depths could have been reached. The temperature cable was installed at this depth and the operation was discontinued for the season on account of the shortage of equipment and because the time alloted for the operation was used up.

Analysis of the Summer's Difficulties

The second season's operations were reasonably successful. In anticipation of the fact that deeper holes would make increased demands on the pumping and water-heating equipment, the purchase of an additional coil heater and a new and stronger pump was recommended. It was also recommended that additional drilling personnel be hired to increase the efficiency of the 24-hour drilling program.

Summer of 1952

Description of the Summer's Work

A new coil heater and a pump capable of operating continuously at pressures of 300 to 400 lb. per square inch were acquired and shipped to Resolute Bay by air. Six men were hired to carry on the operation, working again under the direction of the writer.

The drill crew arrived at Resolute during the first week of July. When the machinery and water circulating systems were re-assembled as they were during the summer of 1951 (see Fig. 4) drilling was commenced, using the same methods which had proved so successful on the 450-foot hole. Two holes were lost due to frost at depths of 682 feet and 512 feet and thus a radical change in method was needed.

With each attempt at deep drilling high pressures were required to keep hot water moving through the drill hole. This is not unusual when drilling soft formations with E equipment, which allows only a small clearance for water passage. However, pressures up to 450 lb. per square inch were used over many shifts and this seemed excessive. In each instance the increase in pressure was accompanied by a decrease in the volume of water being circulated. It therefore seemed probable that the first step towards developing a successful technique might be to reduce this high pressure and to increase the volume of hot water being circulated through the drill hole.

Drilling began on the third hole with these ideas in view. When the pressure gauge on the circulating pump indicated 300 lb. per square inch the drill rods were pulled out of the hole. A pilot-reaming assembly was then sent down on the end of the E rods to ream the hole from a diameter of about 1½ inches to 1⅞ inches. The pilot-reaming assembly was made from a 24-inch AXT core barrel, complete with core bit and reaming shell, with a 3-foot length of E drill rod pinned inside the barrel and welded into the E-rod-to-AXT-barrel adapter. The short length of E rod preceding the AXT bit prevented the reaming assembly from wandering off the prepared hole. The results of reaming were immediately apparent. The pressure indicated at the circulating pump dropped from 300 lb. per square inch to about 150 lb. per square inch, while the volume of water being circulated was increased from 150 to 175 gallons per hour to around 300 to 350. This method was continued by drilling ahead 50 feet with a non-coring bit and then reaming the new ground with the AXT assembly.

Each section of hole was drilled twice when applying the reaming procedure, consequently the ground was exposed to the hot water for longer intervals before new and unheated ground was penetrated. Washing lasted from 1 to 2 hours before extracting the rods for reaming. Little time was devoted to washing the hole after the reaming bit reached bottom. At no time was ice encountered in the hole when re-lowering the rods, though circulation may have been discontinued for over an hour. So successful was the new method that core samples were taken over lengths from 5 to 10 feet at intervals of 50 feet, beginning at the 300-foot level and continuing down to 600 feet.

Just when fortune seemed to favour the completion of the third hole attempted in the 1952 season, the drill rods were seized by pieces of caving rock as they were being lowered to a depth of 660 feet. Attempts to free the rods by using the swivel head as a jack to raise and lower the rods, or by jarring them loose with the stand-pipe, were unsuccessful. A fourth hole was drilled to a depth of 740 feet using the reaming method. Then the threads on one of the drill rods stripped. The rods were hoisted to determine the reason for the sudden pressure drop indicated at the circulating pump. The decrease in pressure was, of course, associated with the rod fracture and 265 feet of drill rod remained in the hole. The season alloted to the project was over and the hole was abandoned.

Considerable time was spent attempting to fish rods from drill holes full of ice. It is interesting to note this change of outlook from previous years when holes and equipment were abandoned when rods were seized by the frost. However, the development of a successful drilling technique should include a satisfactory means of recovering equipment from the frozen ground. Late in the summer it became evident that rods and casing with left-hand threads were required to recover the right-hand equipment stuck in the drill holes.

At first it might seem that right-hand rods and adequate quantities of right-hand EX casing could be used to ream over the frozen E rods. As soon as the ice holding the rods was melted through the circulation of hot water, it should have been a simple matter to raise the string of rods. In practice, drilling with lengths of EX casing in excess of 50-75 feet is hazardous under the best of conditions as the casing is made from a thin wall tubing which spreads easily and bulges at the joints when subjected to strenuous usage. Occurrences of this kind must be avoided when drilling with hot water in frozen ground, as the expansion of the casing joints may cause a reduction in the volume of hot water being circulated through the hole, which in turn could mean the loss of the casing to frost.

However, 40- to 60-foot lengths of EX casing can be used successfully to thaw the top 4 or 5 drill rods. Drilling will not be required for more than the bottom 50 feet of the hole when the reaming procedure has been used. Left-hand rods with left-hand casing can, therefore, be employed to thaw, and turn off, from 1 to 6 of the top rods belonging to the frozen string. The cycle is repeated until the hole is clean and drilling can be recommenced.

Analysis of the Summer's Difficulties

The technique of reaming the hole to AXT size at regular intervals as drilling progressed allowed more water to be placed in contact with the formation and allowed it to be thawed more rapidly. This procedure apparently overcame the difficulties due to frost action, for the failure on the last two holes was due to equipment failure rather than to the freezing of the rods. The E equipment was proving to be too light for the difficult drilling being encountered.

It did not seem feasible to replace all the drilling equipment with the heavier A equipment, but still all the parties concerned were reluctant to abandon the project without a final effort.

Summer of 1953

Description of the Summer's Work

All the co-operating organizations were agreed that this would be the last season they would devote to the project. It was therefore decided that an effort would first be made to reopen the 740-foot hole and to fish out the drill pipe lost in it during the previous summer. If this were successful, a temperature-measuring element would be placed in the hole immediately, so that a limited objective could be accomplished. Only then would an attempt be made to drill to the 1,000 feet originally proposed. If the fishing operation were not successful, a hole would be drilled and a temperature element placed at any depth in excess of 600 feet at which difficulties threatened. Following this the 1,000-foot hole would be attempted if time permitted. Accordingly, equipment was assembled during the winter, and sent to Resolute in the spring airlift.

In preparation for the fishing operation a large amount of special fishing equipment was sent in, including AX flush-joint casing for washing over the drill pipe, a tapered rod tap, a tapered coupling tap, left-hand rod spears, outside or "bell" taps and bit and reaming shell taps. To prepare for the actual drilling, oversized diamond-set bits and reaming shells were ordered to bore holes of extra large diameter. It was hoped that the larger hole would relieve pump pressure. The dimensions of these oversize items as compared with their standard counterparts are shown in the following table:—

	Reaming Shell O.D. Inches	Bit O.D. Inches
Oversize diamond set Items........	1·550 ± ·005	1·535 ± ·005
Standard EXT diamond set Items..	1·485 ± ·005	1·460 ± ·005

The drilling party arrived by air on June 25. The party worked under the supervision of the writer.

When the drill and pumping and water-heating equipment was assembled and checked an attempt at the fishing operation was begun. A drill rod was cut off at an angle and used for washing out the 465 feet of ice above the rods frozen in the 740-foot hole. Washing progressed at the rate of 10 feet per hour to the top of the rods and was continued for 12 hours before attempting to lower the fishing tools. The fishing assembly consisted of 465 feet of left-hand rods terminated by a 10-foot length of left-hand casing with a left-hand rod tap threaded into the rod-to-casing adapter. After removing the rods used for washing, the left-hand equipment was lowered into the hole but was stopped by cave at 200 feet. When repeated drilling through the caved region failed to clear the hole the casing was replaced by a piece of ⅜-inch pipe, which was pinned to the leading end of the tapered rod tap. This small rod was no more successful in penetrating the cave than the casing. As quick setting cement had proved of little use and since there was insufficient casing to case the entire hole, fishing was abandoned in favor of drilling a new hole to 700 feet.

The drilling rig was moved 30 feet away in preparation for the drilling. The hole was collared with 7 feet of 2½-inch pipe seated on bedrock and 100 feet of AX casing. A device for drilling and reaming in one operation was made by coupling a 5-foot EXT core barrel in front of a 2-foot AXT barrel. The leading barrel was fitted with an EXT solid face bit and reaming shell, while the AXT barrel was fitted with an AXT core bit and AXT reaming shell. At depths greater than 500 feet, the EXT bit and reaming shell were replaced by the oversize diamond set items as an additional safety measure.

Drilling progressed smoothly to a depth of 687 feet. At this depth a marked increase was noted in the pressure required to circulate water through the hole, suggesting that the rods were not turning freely. The bit was run up and down through an 18-inch travel in an effort to free the rods and lower the water pressure. In the process of this operation a rod coupling was sheared, leaving 527 feet of "E" rod and the reaming bit in the hole. The fishing operation was started at once but after recovering 230 feet of rod, cave prevented successful continuation of the operation. There was no alternative but to start a new hole.

The second hole was drilled to 675 feet when similar trouble developed. After trying to reduce the water pressure by running the bit up and down in the hole, an attempt was made to hoist the rods, but they were jammed tight. The rods were turned back and 495 feet came free, leaving 180 feet of rod to fish. This time the hole was free from caving material and left-hand fishing tools were quickly brought on top of the rods. It required about one hour to wash a 10-foot length of casing over a frozen rod. The hole was then washed for an additional half-hour before seating the left-hand tap and backing off the top right-hand drill rod. When a rod coupling and drill rod were retrieved together, fishing progressed at the rate of 10 feet every two hours. On several occasions an extra trip was made to retrieve a rod coupling only. The necessity of making these extra trips might well have been avoided if each rod coupling had been pinned or welded to its respective rod. This procedure was repeated without mishap until the hole was 655 feet deep. At this time a 5-foot drill rod was used to carry a multi-element temperature cable down to 650 feet.

As the summer season was almost over and the possibility of drilling a 1,000-foot hole seemed remote, it was decided that the remaining time should be spent attempting to instal a temperature cable under the ocean. This was to be accomplished by drilling a 300-foot hole at an angle of 45° from a set-up 10 or 20 feet from the ocean. A standard EXT core barrel with oversize reaming shells and oversize solid face bits was used without the AXT barrel and with complete success. The clearance provided by the oversize bit and shell was adequate to permit the circulation of almost as much water as was previously used with the reaming assembly.

The hole was put down to 300 feet after 2 days drilling. When hoisting the rods a considerable quantity of cave was indicated over the lower two-thirds of the hole. These suspicions were confirmed when attempting to instal the temperature cable, which could not be worked down past 115 feet.

Analysis of the Summer's Difficulties

The pattern of difficulty in the 2 holes which were lost during the season was remarkably similar. In both cases pressure built up suddenly, and when an attempt was made to lift the rods they jammed in the hole and broke off. It is not clear how much of this difficulty was due to frost action and how much to the caving character of the formation. The temperature of the circulating water was probably close to freezing at the face of the bit so that a limit had about been reached for the use of hot water. It is difficult to be certain about this because the drill rods, which are being heated by the hot water flowing inside them, are in turn heating the water flowing back over their outer surfaces.

DISCUSSION AND CONCLUSIONS

In this section the difficulties encountered throughout the project are re-examined with a view to recommending a procedure which may help others contemplating similar work. These difficulties arise from the following basic problems:—

1. Frost action, with the consequent necessity of heating water.
2. Circulation difficulties.
3. Caving formations which mud the bit.
4. Failure of equipment.

Frost Action

This is the fundamental difficulty, and modifies all other problems. Aside from the difficulty of heating the water the use of hot water imposes a severe strain on the pumps, subjects the drillers to the danger of severe burns in the event of a hose failure, and prevents the efficient use of rod lubricants. This in turn results in excessive vibration of the rods with correspondingly excessive wear on equipment. Finally, the presence of the frost means that any small delays in the drilling operation, which are extremely difficult to avoid in practice, are likely to result in the freezing of the rods.

The heating system adopted at the beginning of the 1951 season, consisting of the commercial marine-type boiler plus a coil-heater operating in series, proved satisfactory, but was probably no more so than a series of 3 or 4 coil heaters would have been and was much more difficult to transport. When the coil heaters are designed so that they can be cleaned without dismantling the heater they give complete satisfaction. The duplicated pumping arrangement shown in Figure 4 proved satisfactory and is a necessity considering the difficulties which can result from even a brief failure of the pumping equipment.

The use of hot water in drilling as opposed to the use of chemicals in the drilling water (discussed later) works very well for the shallow holes. If water is circulated for some time prior to removing the rods the hole will remain ice-free long enough to allow minor repairs to the rig. This is borne out by an experiment conducted during the 1951 season. A hole was drilled to a depth of 115 feet with a bull-nosed bit in 9 hours, then washed with hot water for one hour. The rate of circulation was 150 gallons per hour, with water entering the rods at about 140°F. and coming back at about 130°F. At the end of this time a temperature element was lowered to the bottom of the hole and the temperatures shown in Table V were recorded. When the rods were returned to bottom, approximately one hour after circulation had stopped, 4 feet of ice had formed in the hole.

TABLE V

Depth of Thermometer in Drill Hole	Time Elapsed Since Circulation Stopped	Temperature in Drill Hole	Temperature in Undisturbed Ground
feet	minutes	°F.	°F.
115	10	60	8
	10¼	56	
	10½	54	
112	5½	67·8	8
	6	67·5	
	8	64·8	
	9½	62·5	
100	11½	58	8
	12	59	
	12½	58·5	
	13	58·2	
	14	57·3	
	15	56·8	
	16	55·7	
	17	55·0	
	18	54·2	
	19	53·4	
	20	52·7	
	21	51·9	
	22	51·3	
	23	50·6	
	24	50·0	
	25	49·2	
	26	48·8	
	27	48·1	
60	30	62·8	8
	31½	62·2	
	32	62·2	
40	33	63·1	10
20	34	65·0	13
	35	63·8	

The temperatures recorded at depths of 115 feet probably represent the trend of the thermometer towards an equilibrium temperature rather than an actual rate of cooling of the hole. Temperatures observed at 112 feet, five to ten minutes after circulation stopped will represent cooling, as will those recorded in the interval 11 to 30 minutes at 100 feet. It is evident that, if the water is circulated for a reasonable period after drilling has been stopped, there will be time to carry out minor repairs if the rods are raised several feet off bottom.

The use of hot water in drilling seems to reach a limit of applicability at about 600 or 700 feet, though the temperature of the water at the face of the bit could not be determined for the reason explained earlier. Conditions elsewhere, of course, may not be so severe as at Resolute Bay. The temperature of $-13° \cdot 5$C recorded at a depth of 50 feet is believed to be the lowest on record, and the temperature gradient obtained as indicated in a preliminary publication[1] suggested that the permafrost has a thickness in excess of 1,000 feet.

Until the middle of the final season it appeared that the use of hot water would provide a satisfactory solution for the frost problem, and for this reason no effort was made to use chemicals in the drilling water to lower its freezing point. Calcium chloride dissolved in the drilling water is being used in regions farther south with considerable success and there is no obvious reason why it might not be successful under more severe conditions. It does not crystalize out except at extremely high concentrations far above anything that would be required, nor does it stratify in a vertical column so that it would not freeze in the top of the hole. For ground temperatures observed at Resolute a concentration of about 1·8 pounds of calcium chloride to one gallon of water would be needed. In order to conserve chemicals, a closed water system with well-designed sludge boxes to remove the cuttings would be required, but this should not be difficult to construct.

CIRCULATION PROBLEMS

Circulation problems, which were responsible for much of the difficulty encountered, derived largely from the use of the small E equipment. Difficulties were reduced considerably by reaming the hole to AXT size either after drilling or with a reamer above the bit, and by the use of over-size bits. These devices would have been largely unnecessary had the larger tools been used from the start.

CAVING PROBLEMS

The mudding off of caving formations, a technique used in oil-well drilling, has only recently been adopted by Canadian diamond drillers. In this project, caving formations, combined with low temperatures provided the major difficulty at depths below 650 feet. Had it been possible to case these formations with AX, or even larger casing and to drill the remainder of the hole with E tools the project would have been simplified. However the original choice of E tools made this impossible.

FAILURE OF EQUIPMENT

Most equipment problems arose from the use of hot water, which imposed a strain on the pumps and which, by dissolving the rod grease, resulted in excessive vibration. Actual failure of equipment would probably have been less serious had heavier A equipment been used.

---

[1] A. Thomson and P. Bremner, *Nature*, *170*, 705, 1952.

Summary

Most of the difficulties met with were due to factors which might have been overcome by the use of larger equipment. Problems due solely to the permafrost were successfully overcome. The water heating and pumping arrangements devised were quite satisfactory. It is probable that for depths below 600 feet the use of chemicals in the drilling water would be necessary to overcome frost action.

The depths of the temperature measuring elements placed throughout the project are summarized in Table VI.

TABLE VI

Disposal of Temperature Elements, by Depth

Height	Depth	Element or Cable Number	Depth	Element or Cable Number
22 m.		1948–2	45 ft.	146
11 m.		1948–3	50 ft.	146, 147
2 m.		1948–4	50½ ft.	1950–4
	0	1948–9, 146, 1950–5, 147	55 ft.	146
	·10 m.	1948–10	60 ft.	146
	·20 m.	1948–12	65 ft.	146
	·42 m.*	1948–7	70 ft.	146
	·45 m.†	1948–11	80 ft.	146
	·85 m.*	1948–8	90 ft.	146
	1·0 m.†	1948–1	100 ft.	146, 147
	1·5 m.†	1948–13	150 ft.	147
	5 ft.	146, 1950–6	200 ft.	147
	10 ft.	146, 1950–1	250 ft.	147
	15 ft.	146	300 ft.	170, 147
	20 ft.	146	350 ft.	147
	21½ ft.	1950–2	400 ft.	147
	25 ft.	146	450 ft.	171, 147
	28 ft.	1950–3	500 ft.	147
	30 ft.	146	550 ft.	147
	35 ft.	146	600 ft.	147
	40 ft.	146	650 ft.	147

*In disturbed ground.
†In holes cased with garden hose.

ACKNOWLEDGMENTS

Acknowledgment is made to the United States Weather Bureau, Air Transport Command of Royal Canadian Air Force and Canadian Longyear Company for invaluable assistance, as well as to drill operators Victor Abel, Ambroise Menard, Harold Lafrange, John Duval, O'Brien Rivard, Lionel Anthier, Andre Sabourin, Paul Gauthier and Erle Kirkwood.

CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
DOMINION OBSERVATORIES

PUBLICATIONS
OF THE
Dominion Observatory
OTTAWA

Vol. XVI, No. 13

Canadian West Coast Earthquakes, 1953

BY

W. G. MILNE

EDMOND CLOUTIER, C.M.G., O.A., D.S.P.,
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
OTTAWA, 1955

600—1955

Canadian West Coast Earthquakes, 1953

BY

W. G. Milne

ABSTRACT

In 1951 the Dominion Observatory began a program of studying the earthquakes of southwestern British Columbia. The present paper lists 150 earthquakes recorded during 1953; this brings to 443 the number of tremors recorded since the inception of the program in August, 1951. The new epicentres are tabulated and plotted on a map of southwestern British Columbia. A detailed map of south Vancouver Island shows all the epicentres recorded in this area throughout the program.

The paper also gives the details of the newly built and newly equipped Victoria station.

INTRODUCTION

This report is a continuation of the investigation of local earthquakes in western sections of Canada. The first report was made for the latter half of 1951[1], and a subsequent list of tremors was published for 1952[2]. Data for locating the epicentres are obtained from the Victoria, Alberni, and Horseshoe Bay seismograph stations, and quite often from neighbouring United States installations.

DESCRIPTION OF STATIONS

A new office building for the Dominion Astrophysical Observatory was completed in June, 1953. This building provides office space and dark-room facilities for the seismological section, as well as much larger vaults than had previously been available. Three component Benioff variable reluctance seismographs were ordered for these new vaults and it was planned to take the existing Benioff vertical to Seven Falls. As it turned out it was necessary to make the transfer to Seven Falls before the new Benioff recorder had been received, so that for some time the Victoria station was without short-period instruments.

The schedule of the move from the old to the new vaults was as follows:

January 1 to July 3	Milne-Shaw horizontal seismographs and original Benioff vertical seismograph operating in old vault.
July 3 to September 6	Milne-Shaw horizontals and new Benioff vertical in new vault.
September 6 to October 23	Milne-Shaw horizontals only recording in new vaults.
October 23 to December 4	Milne-Shaw horizontals in new vault. Benioff vertical seismometer ($T_s = 1$ sec.) recording through Leeds and Northrup galvanometer ($T_g = 1\cdot9$ sec.) in new vault. Magnification unknown, microseisms very large.
December 4 to December 31	All new seismometers (3 component Benioff short-period only) and Milne-Shaw horizontals recording in new vault.

---

[1] W. G. Milne and F. Lombardo, "Canadian West Coast Earthquakes, 1951", *Publications of the Dominion Observatory*, Vol. XVI, No. 3, 1952.

[2] W. G. Milne, "Canadian West Coast Earthquakes, 1952", *Publications of the Dominion Observatory*, Vol. XVI, No. 9, 1953.

The operation from December 4th on has been as intended for the permanent installation. The Milne-Shaw seismographs, being long-period instruments, are of use primarily in recording teleseisms, not the local tremors reported here. The short-period Benioff seismographs are operated conventionally, ($T_s = 1$ sec., $T_g = 0 \cdot 2$ sec.). Damping during the period covered by this paper was slightly less than critical, and the gain is set at about $\frac{2}{3}$ scale, which is the limit allowable because of microseismic amplitudes. It is estimated that this represents magnification of 10,000 to 15,000.

There has been no change in the timing arrangements at Victoria. Time marks are placed on the records by a pendulum clock. Time signals from NPG (San Francisco) are recorded, when they can be received, at 0^h, 6^h, 12^h, and 18^h G. M. T.

The new vault is some distance removed from the previous one. This has necessitated the redetermination of the station co-ordinates. The two sets of co-ordinates, as well as those of Alberni and Horseshoe Bay, are given in Table I.

TABLE I

Station		Latitude	Longitude
		° ′ ″ N	° ′ ″ W
Victoria	1 Jan. to 3 July	48 31 14	123 24 56
Victoria	4 July to 31 December	48 31 09·9	123 24 55·1
Alberni		49 16 14	124 49 18
Horseshoe Bay		49 22 39	123 16 33

At Alberni the instrumentation is the same as that installed in 1951. Willmore-Sharpe seismometers record through Turner galvanometers on a Sprengnether three-component recorder. Canadian Broadcasting Corporation time signals from the Dominion Observatory, Ottawa, are placed on the records automatically at 18^h G. M. T. WWV signals are usually put on, in addition, at 3^h. At Horseshoe Bay the instrumentation is now the same as at Alberni. At both stations T_s is approximately $\frac{1}{3}$ sec. and T_g is about $\frac{1}{30}$ sec. In both locations the instruments are very sensitive to traffic noise.

The time signals broadcast over CBU, Vancouver, by the Canadian Broadcasting Corporation, and recorded at Alberni and Horseshoe Bay, are carried from Ottawa to Vancouver by wire. The NPG signals recorded at Victoria are received directly from San Francisco by short-wave receiver. The fact that these two signals travel to the seismic network by two different media raised the question whether there might be a small difference between the two time standards used.

An opportunity arose of recording both CBU and NPG signals on a single record. Within the limits imposed by the slow paper speed of 60mm/min. no difference in the two sets of signals could be detected. Since this is the paper speed normally used within the network there can be no error in the epicentre locations due to the difference in timing standards.

1953 EARTHQUAKES

EPICENTRE LOCATION

The system of epicentral location described in the 1951 paper is still in use. The charts used are still based on velocities determined in the Canadian Shield. Current investigations suggest that these velocities are appropriate.

The earthquakes recorded at each of the three stations (Alberni, Horseshoe Bay and Victoria) during 1953 are listed in Table II. The earthquakes are numbered consecutively with those of the two earlier papers. Epicentres have been given where possible. Epicentres of earthquakes off the coast located by the United States Coast and Geodetic Survey have been included in the table even though the data from the Canadian stations were not sufficient to allow a location.

All the epicentres regarded as dependable have been plotted on the attached map of southern British Columbia.

DETAILS OF PARTICULAR EARTHQUAKES

Yukon Tremors

Table II lists three earthquakes originating in the Yukon. It seems desirable that these should be included in the report, but it must be stressed that the Yukon is so far from the existing network of stations that only the very largest shocks from that area can be included.

The strongest of these Yukon earthquakes, with a magnitude of 6½, occurred on January 11. The United States Coast and Geodetic Survey places the epicentre at 65°N, 133°W. We have had a report that at Mayo, some 130 miles southwest of this epicentre, buildings and telephone poles swayed, but without damage to any installations. Mayo appears to be the nearest settled point to the epicentre.

Kitimat Landslide

The seismographs did not record a series of events which occurred in the Kitimat project at about 6:30 a.m., P.S.T., on September 1. A report in the Prince Rupert newspaper is the source of the following information.

The event began with a slight tremor, sufficient to shake quite heavy objects. However, the felt area seemed to be not larger than the camp itself. An operator of a tractor working along the road, noticed the earth moving like a wave, and cracks opening in the ground. He had difficulty making his way to safety as the whole road was crumbling underfoot. There was a long crack in the earth striking from west to east, and some piling was moved 100 feet across a clearing. Further mention is made of a small tremor being felt about 6 hours before the slide.

The main damage of this event seems to be confined to a very small area, and to be connected with a landslide or subsidence. However, evidence does indicate that a slight tremor may have been the trigger to start the earth movement. It would not be surprising if, when instrumental coverage permits a study of this whole coastal area, it is found that many such small tremors exist at the heads of inlets similar to this and quite like those already being recorded from Jervis Inlet, farther south.

Ferguson

One person in the area of Ferguson reported that an earthquake was felt there on February 3rd at about 3 a.m. P.S.T. This area is in eastern British Columbia just east of Upper Arrow Lake, in the Columbia River drainage basin.

DISCUSSION OF EPICENTRES

There are several points worth noting in the distribution of the 1953 epicentres. The first concerns the concentration of epicentres in the vicinity of Jervis Inlet (Nos. 409, 422, 423, 439 and 440). None of these earthquakes were large, but a trend first noted in the 1952 earthquakes is being continued. Epicentres 77, 206, 247, and 284, listed in the 1952 report, were in the same area.

Another outstanding feature of this year's activity is the number of moderately heavy tremors off the west coast of Vancouver Island. The tables show a total of 26 earthquakes in this area. Of these, 345 and 435 are the major events, the latter being of intensity at least VI. It is clear that there is a well marked area of seismic activity at some distance west of Vancouver Island, and that the intensity of events in this area is currently greater than that nearer the continent.

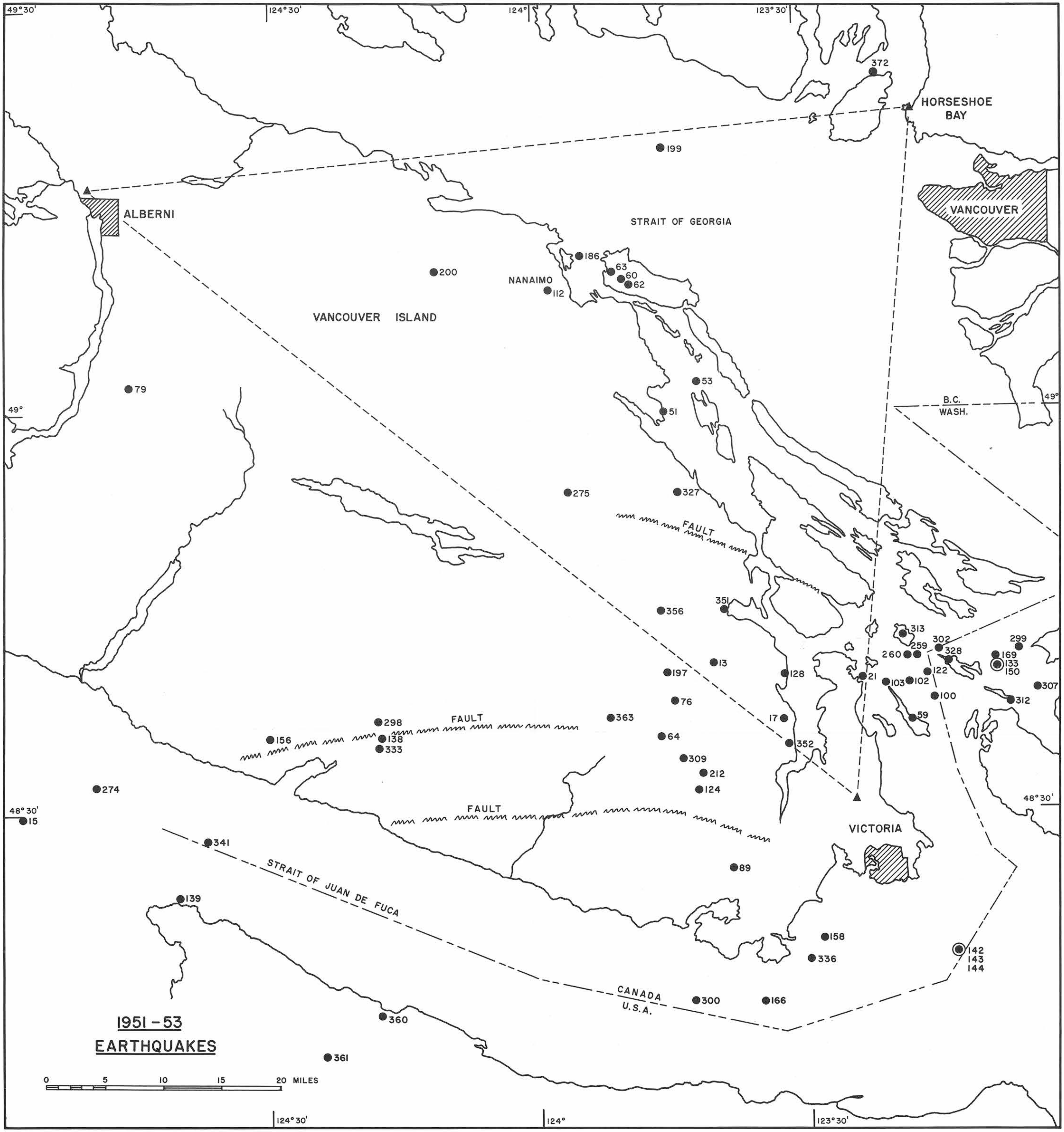
The majority of the earthquakes located seem to occur towards the southern end of Vancouver Island. The attached map shows all the epicentres located in this area since the inception of the program. The concentration of epicentres in this area may be partly due to the location of the stations but it must be largely real. The Victoria area is no more favoured by the location of the stations than the other points of the triangle.

In earlier reports it was noted that the epicentres in this area seemed to define rough lines, which might be considered to correspond to active faults. This tendency seems to be continuing, but until more evidence has accumulated no final conclusions can be drawn.

ACKNOWLEDGMENTS

Once again, thanks are due to those United States seismograph stations who have co-operated in the location of many of the epicentres listed here. Readings from Butte, Hungry Horse and Seattle have often been used, and the kindness of their seismologists in supplying them is greatly appreciated.

Dominion Astrophysical Observatory,
Victoria, B.C.,
March 7, 1955.



1951 – 53
EARTHQUAKES

TABLE 2—1953 EARTHQUAKES

No.	Date	Origin Time GMT	Lat. N.	Long. W.	Intensity	Arrival Times of P-Phase, GMT			Distance			Remarks
						Victoria	Horseshoe Bay	Alberni	V	HB	A	
			° ′	° ′						kms		
293	Jan. 7				I	13 07 19·6	13 07 32·8				96	Probably west of Bowen Island in Howe Sound.
294	Jan. 8	05 26 04	47·5	124·5	III	05 26 19·9	05 26 30·9	05 26 29·0	95	197	182	In western Washington State.
295	Jan. 11		65	133		22 57 38			1850			U.S.C.G.S. epicentre in Yukon, Mag 6½–6.
296	Jan. 13				II	04 19 52·6		04 19 28·5			430	Possibly northwest of Alberni.
297	Jan. 13				II	15 29 38·1	15 29 49·6					Probably near Seattle, Washington.
298	Jan. 15		48 37	124 18	II	07 00 51·3	07 00 59·2	07 00 53·7	84			Near No. 138 (1952) southwestern Vancouver Island.
299	Jan. 20	06 54 05	48 42	123 06	III	06 54 11·2	06 54 18·5	06 54 29·1	34	78	143	Waldron Island.
300	Jan. 30	18 43 47	48 16	123 43	II	18 43 52·9	15 44 07·7	18 44 09·2	38	130	140	Strait of Juan de Fuca.
301	Jan. 30				I		22 24 33·4		38			Strait of Juan de Fuca.
302	Feb. 2		48 42	123 15	II	17 41 30·4	17 41 38·6	17 41 47·4	23	77	131	Gulf Islands—Victoria P/S amplitude approx. 2/1.
303	Feb. 3	11 18 33	50 18	116 55	III	11 19 44·7	11 19 37·3	11 19 54·0	536	496	608	Felt at Ferguson, B.C. Epicentre near Duncan Lake.
304	Feb. 12					01 31 29						Yukon.
305	Feb. 12					04 35 25						Yukon.
306	Feb. 20				I	00 52 27·0		00 52 16·4	113			Probably south of Alberni near canal.
307	Feb. 20		48 39	123 04	II	05 16 38·7	05 16 46·8	05 16 57·0	31	81	146	Gulf Islands.
308	Feb. 20							08 40 44·4			83	Off west coast of Island.
309	Feb. 21		48 34	123 44	III	11 26 39·0	11 26 50·6	11 26 52·7	25	98	111	South Vancouver Island.
310	Feb. 24				IV	19 40 30·7	19 40 42·1	19 40 52·8	128	243	293	Felt in Seattle, Washington.
311	Feb. 25				II	01 59 04·8	01 59 16·9					May be near No. 310.
312	Feb. 25		48 38	123 07	III	09 29 23·9	09 29 33·3	09 29 42·9	26	86	144	Gulf Islands.
313	Feb. 27		48 43	123 19	II	20 44 37·7	20 44 45·8	20 44 53·9	22	76	126	Gulf Islands.
314	Mar. 4				I			09 34 15·8			72	
315	Mar. 4				I	18 32 53·5			11			Felt in Victoria.
316	Mar. 7				I			17 02 31·4			58	
317	Mar. 7				I	21 56 08·4			17			
318	Mar. 8				II−	06 31 41·1	06 31 51·7		148			Near Seattle?
319	Mar. 8				II+	21 54 25·9	21 54 38·6	21 54 40·6	120	226	248	In western Washington State.
320	Mar. 10		47·5	123·5	II+	00 02 04·7	00 02 19·9	00 02 16·9				In western Washington State.
321	Mar. 12				II−			00 45 34·4			79	

TABLE 2—1953 EARTHQUAKES—*Continued*

No.	Date	Origin Time GMT	Lat. N.	Long. W.	Intensity	Arrival Times of P-Phase, GMT			Distance			Remarks
						Victoria	Horseshoe Bay	Alberni	V	HB	A	
			° ′	° ′						kms		
322	Mar. 12	19 04 11	49 12	122 54	III−	19 04 24·9	19 04 16·8	19 04 33·2	83	31	142	In Fraser River south of New Westminster, probably blasting.
323	Mar. 13	...	...	...	I	01 30 36·2	...	...	14			
324	Mar. 14	00 58 23	49 00	122 12	II	00 58 40·6	00 58 38·6	00 58 53·8	103	91	193	Sumas Mountain, B.C.
325	Mar. 17	...	...	...	I	...	...	06 01 00·1			10	
326	Mar. 22	20 15 57	48 52	125 15	III	20 16 19·3	20 16 22·0	20 16 06·3	140	156	57	Entrance to Barkley Sound.
327	Mar. 23	07 03 08	48 54	123 44	II	07 03 26·8	07 03 38·9	07 03 43·4	46	62	91	Near Chemainus, Vancouver Island.
328	Mar. 25	16 52 00	48 41	123 14	III−	16 52 04·6	16 52 13·0	16 52 22·0	22	77	134	Gulf Islands.
329	Mar. 27	...	...	...	I	...	...	22 37 51·8			14	
330	Mar. 28	...	...	...	I	...	22 13 14·3	...		48		
331	Mar. 31	...	...	...	I	...	20 46 33·2	...		12		
332	April 2	...	...	...	I	...	...	00 27 41·1			72	
333	April 2	07 58 33·5	48 35	124 18	II+	07 58 46·2	07 58 53·9	07 58 47·4	73	126	81	Southwest Vancouver Island.
334	April 8	...	...	...	I	...	...	04 56 26·9			72	
335	April 8	...	...	...	I	21 18 34·8	...	...	8			
336	April 8	22 44 09·7	48 19	123 30	II	22 44 14·8	22 44 28·9	22 44 33·1	24	115	150	South of Victoria in Strait of Juan de Fuca.
337	April 9	...	...	...	II−	00 27 31·7	...	00 27 23·6	213		79	Off west coast of Vancouver Island.
338	April 10	11 06 27·8	...	...	III	11 16 52·7	11 07 05·3	11 07 04·1	168	272	242	South in Washington State.
339	April 15	...	...	...	I	04 55 33·5	...	...	104			
340	April 15	...	...	...	I	14 32 35·4	...	...	118			
341	April 15	21 35 33·5	48 28	124 37	II+	21 35 48·7	...	21 35 49·4	89		94	Entrance to Strait of Juan de Fuca.
342	April 19	...	...	...	II	09 36 01·6	...	09 36 19·6	137		290	Probably in Puget Sound area.
343	May 4	...	48·0	124·3	II+	00 44 38·6	00 44 51·3	00 44 49·4	92	174	145	Western Washington State.
344	May 14	...	...	...	I	01 46 47	...	...	...	...	...	Same general area as No. 345.
345	May 14	07 41 44	50	130	IV	07 42 52	...	07 42 36·3	500		371	Off west coast of Vancouver Island, U.S.C.G.S. location.
346	May 14	18 27 41	50	130	IV	18 28 52	...	18 28 37·2	518		405	Off west coast of Vancouver Island.
347	May 20	23 14 23	50	130	IV	23 15 33·0	...	23 15 22·4	495		340	Off west coast of Vancouver Island.
348	May 21	12 29 51	50	130	IV	12 31 00·0	...	12 30 47·1	490		375	Off west coast of Vancouver Island.
349	May 23	...	...	...	I	...	...	10 04 32·8			89	
350	May 24	...	...	...	I	...	...	04 38 13·9			76	
351	June 2	22 07 58	48 45	123 39	II−	22 07 03·5	22 07 10·6	22 07 15·4	28	75	105	South Vancouver Island.
352	June 4	00 11 03	48 35	123 32	II+	00 11 06·4	00 11 18·5	00 11 23·3	11	91	122	South Vancouver Island.

353	June	9	....	....	....	II	18 48 25	....	18 48 13·0	......	......	......	Probably off west coast.
354	June	9	....	....	....	II	23 30 03·5	....	23 29 43·5	......	......	......	Northern Vancouver Island.
355	June	11	23 37 32	49 49	123 52	III	23 37 55·5	23 37 42·5	23 37 46·8	148	63	90	Sechelt Peninsula area.
356	June	16	17 53 20	48 45	123 46	III−	17 53 27·0	17 53 33·8	17 53 36·9	34	78	98	South Vancouver Island.
357	June	19	....	....	....	II	22 52 23·8	....	22 52 23·6	......	......	......	Off west coast.
358	June	27	07 09 17	48·6	125·7	II+	No Time	07 09 48·5	....	176	202	99	Off west coast–Victoria S–P readable.
359	July	4	....	....	....	......	No Time	....	10 00 12·9	......	......	......	Off west coast.
360	July	5	13 55 07	48 15	124·3	III	No Time	13 55 32·4	13 55 26·1	63	139	115	Western Strait of Juan de Fuca.
361	July	6	09 48 34	48·2	124·4	II	No Time	09 48 58·4	09 48 52·5	80	149	114	Northwest Washington State.
362	July	11	08 13 30	48 14	122 52	III+	08 13 37·7	08 13 50·6	08 13 58·3	52	130	184	Entrance to Puget Sound.
363	July	17	08 57 45	48 37	123 52	II+	08 57 51·6	08 58 00·6	08 58 01·7	35	94	100	Southern Vancouver Island.
364	July	18	....	....	....	I	22 29 44·7	....	....	......	......	......	
365	July	21	....	....	....	III	08 54 00·6	....	....	......	......	......	
366	July	22	10 17 39	48·5	128	IV+	10 18 32·4	....	10 18 22·4	425		326	U.S.C.G.S. location.
367	July	22	....	....	....	III	10 37 05·0	....	10 36 55·8	......	......	......	Probably off west coast.
368	July	22	10 37 20	48·5	128	IV+	10 38 13·0	....	10 38 03·3	415		330	U.S.C.G.S. location.
369	July	26	....	....	....	II	17 47 50	....	17 47 28·3	......	......	......	Off west coast.
370	July	28	....	....	....	II	18 49 08	....	18 48 50·1	......	......	......	Off west coast.
371	July	29	06 00 48	49·3	122·4	II	....	06 00 58·4	06 01 15·2		59	173	Due east of Horseshoe Bay between Pitt and Stave Lakes.
372	Aug.	1	05 33 10	49 25	123 21	II	05 33 27·7	05 33 12·7	05 33 28·7	102	8	108	Between Gambier and Bowen Islands, Howe Sound.
373	Aug.	4	10 26 22	48·3	129·1	IV+	10 27 17·3	10 27 20·5	10 27 06·5	420	437	325	Off west coast.
374	Aug.	4	....	....	....	II	....	....	10 54 13·4	......	......	......	Same as No. 373.
375	Aug.	4	....	....	....	II	....	....	11 08 31·3	......	......	......	Same as No. 373.
376	Aug.	4	11 35 27	47·9	128·7	IV	11 36 25	11 36 25·2	11 36 11·0	400	427	320	Off west coast.
377	Aug.	6	....	....	....	I	23 29 26·7	....	....	......	......	......	
378	Aug.	9	....	....	....	I	....	05 50 43·9	....	......	......	......	Very close to Horseshoe Bay.
379	Aug.	10	11 22 25	48 50	122 55	III	No Time	11 22 34·5	11 22 49·2	49	60	146	Strait of Georgia.
380	Aug.	16	....	....	....	II	06 15 45·1	....	06 15 56·9	......	......	......	Probably off west coast.
381	Aug.	20	18 32 41	47·8	123·8	III	18 32 52·9	....	18 33 08·9	79		173	In Olympic Mountains.
382	Aug.	20	....	....	....	I	....	....	20 37 24·5	......	......	......	
383	Aug.	21	....	....	....	I	....	....	23 51 12·0	......	......	......	
384	Aug.	26	....	....	....	I	....	....	23 23 03·1	......	......	......	Nos. 382, 383, 384 are alike in appearance.
385	Aug.	29	....	....	....	I	04 30 43·0	....	....	......	......	......	
386	Aug.	31	....	....	....	I	04 46 24·7	....	....	......	......	......	
387	Sept.	4	....	....	....	II	18 44 46·7	....	18 44 24·2	......	......	......	Probably in Washington.
388	Sept.	7	....	....	....	I	23 29 32·8	....	....	......	......	......	
389	Sept.	8	....	....	....	I	00 12 38·6	....	....	......	......	......	
390	Sept.	8	....	....	....	I	11 42 25·5	....	....	......	......	......	
391	Sept.	8	....	....	....	I	11 54 04·9	....	....	......	......	......	
392	Sept.	10	....	....	....	I	....	....	14 36 43·8	......	......	......	

TABLE 2—1953 EARTHQUAKES—*Concluded*

No.	Date	Origin Time GMT	Lat. N.	Long. W.	Intensity	Arrival Times of P-Phase, GMT			Distance			Remarks
						Victoria	Horseshoe Bay	Alberni	V	HB	A	
			° ′	° ′						kms.		
393	Sept. 12				I			19 09 25·4				
394	Sept. 13				I			00 12 05·3				
395	Sept. 15				I			19 10 00·3				
396	Sept. 19				I			23 30 40·1				
397	Sept. 23				I			21 30 09·3				
398	Sept. 23				I			21 58 49·3				
399	Sept. 23				I			21 59 37·9				
400	Sept. 25				I			21 10 02·9				
401	Sept. 29				I		15 59 12·8			123		
402	Sept. 29				II		16 31 15·1	16 31 15·3		210	211	Probably south.
403	Sept. 30				II		19 36 28·9	19 36 31·1		114	132	
404	Sept. 30				I			22 22 54·5			66	
405	Oct. 1				I			09 00 26·3			50	
406	Oct. 2				I			00 27 17·0			80	
407	Oct. 2				I		06 11 00·9			74		Probably in Sechelt area.
408	Oct. 4				I			07 43 30·9			34	
409	Oct. 4	19 41 14	50·0	123·5	III		19 41 28·9	19 41 32·4		76	116	Probably in Sechelt area.
410	Oct. 8				I			18 59 49·9			72	
411	Oct. 10				I			23 59 56·4			54	
412	Oct. 11				I			11 44 41·0			94	
413	Oct. 12				I			17 54 17·9			52	
414	Oct. 13				I			08 28 08·0				Off west coast?
415	Oct. 13				II			08 56 30·9				Off west coast?
416	Oct. 13				I			15 26 58·6			460	
417	Oct. 13				I			17 13 28·8			325	
418	Oct. 13				I			21 30 57·7			74	
419	Oct. 21				I		S–P only	06 57 37·4		100	130	North of Sechelt?
420	Oct. 27				I			15 44 50·4			48	
421	Oct. 29				I			04 20 02·8			76	
422	Oct. 31	00 10 58·6	49·9	123·5	II		00 11 11·6	00 11 17·3		68	111	North of Sechelt?
423	Oct. 31	16 29 43·5	49·9	123·5	II		16 29 54·8	16 30 01·9		64	109	North of Sechelt?
424	Nov. 2				II			01 59 32·3			108	
425	Nov. 3				I			08 13 58·1			66	
426	Nov. 4				I		11 26 10·8	11 26 18·9			110	North of Sechelt?

427	Nov. 7	....	....	....	I	....	....	22 53 23·6			58	
428	Nov. 9	....	....	....	II	S–P only	....	22 09 31·9	84		110	Western Olympics?
429	Nov. 18	....	....	....	I	....	10 25 50·7	....		37		
430	Nov. 20	....	....	....	I	....	06 31 42·6	....		20		
431	Nov. 23	....	....	....	I	....	10 45 27·0	....		13		
432	Nov. 27	....	....	....	II	trace	....	22 53 18·3			310	Off coast.
433	Nov. 29	23 50 39	....	....	II	S–P only	23 51 07·8	23 51 07·8	86	172	196	Entrance to Puget Sound?
434	Dec. 1	20 15 44	....	....	I	S–P only	....	20 16 05·6	25		135	
435	Dec. 4	14 54 46	49·5	129	VI	....	14 54 51·5	14 54 34·4			375	U.S.C.G.S. location, registered at distances out to 80°.
436	Dec. 6	....	....	....	I	....	06 01 55·6	....		58		
437	Dec. 12	....	....	....	I	trace	....	08 05 33·7			370	Off west coast?
438	Dec. 12	08 28 36	49·5	129	III	08 29 44·9	....	08 29 28·7	430		375	Off west coast?
439	Dec. 12	09 47 27	49·7	123·4	II	....	09 47 36·5	09 47 46·5		50	116	Northeast of Sechelt.
440	Dec. 12	12 20 18	49·7	123·4	II	....	12 20 27·7	12 20 37·8		52	114	Northeast of Sechelt.
441	Dec. 12	....	....	....	I	17 41 00	....	trace	....	....	....	Off west coast.
442	Dec. 16	....	....	....	I	04 32 39·8	....	trace	....	....	....	
443	Dec. 20	11 35 33·2	48·6	121·8	III	11 35 45·8	11 35 48·8	11 36 01·3	70		190	East of Bellingham.

CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
DOMINION OBSERVATORIES

PUBLICATIONS
OF THE
Dominion Observatory
OTTAWA

VOL. XVI, No. 14

CHARTS FOR MEASURING AZIMUTH AND DISTANCE and for TRACING SEISMIC RAYS THROUGH THE EARTH

BY

P. L. WILLMORE AND J. H. HODGSON

EDMOND CLOUTIER, C.M.G., O.A., D.S.P.
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
OTTAWA, 1955

600—1955

Charts for Measuring Azimuth and Distance and for Tracing Seismic Rays Through the Earth

BY

P. L. Willmore and J. H. Hodgson

ABSTRACT

The paper presents two charts which are of help in seismology. With the aid of the first chart the distance between any two points on the earth and their relative azimuths can be determined with an accuracy sufficient for most seismological problems. The second chart enables one to trace rays through the earth's mantle, and is of help in studies which involve the relationship between depth of penetration and point of emergence. It is used to exhibit a complicated cusp arrangement associated with the phase pP.

Additional copies of both charts, mailed unfolded, may be obtained from the authors.

INTRODUCTION

This paper will present two charts which have been found useful in the seismological work of the Dominion Observatory. One of them is a stereographic net for the determination of azimuths and distances. The other is a diagram, based on the structure of the earth as determined by Jeffreys and Bullen, tracing ray paths penetrating to various depths. The diagram can be used very efficiently in any problem involving ray tracing, and the method described can be applied to other postulated structures.

Neither of the matters treated involve very much original work. However the draughting of the charts is so complicated that it seems worthwile to make our charts available to all. These have been drawn by Mrs. I. H. Blüme, of the Observatory staff. Our very sincere thanks go to her for her painstaking and skillful work.

THE USE OF THE STEREOGRAPHIC NET FOR DETERMINING AZIMUTH AND DISTANCE

STATEMENT OF THE PROBLEM

Direct computations of the distance and azimuth between pairs of points on the earth's surface become tedious when large bodies of data have to be reduced. In approximate work, distances are often measured by stretching a tape over the surface of a globe, but the method is clumsy, and its accuracy is often limited by the absence of a sufficiently close network of parallels and meridians. Recently, Tsuboi (1951) published a simple and rapid method for finding the distances from a fixed station to any number of other points on the earth's surface, but his device contains a nomogram which has to be redrawn for each station. Moreover, azimuth cannot easily be measured either on the globe or by Tsuboi's method.

At the Dominion Observatory, interest in the direction of faulting in earthquakes has raised the problem in an acute form, for a single fault plane reduction may require a knowledge of the distance and azimuth from an earthquake epicentre to a hundred or more recording stations. Until recently, the computations were made on an electronic machine at considerable expense, but with the aid of Chart I, the results can be obtained rapidly, to an accuracy which is fully comparable with that of the original data. The chart is similar to that which is used for the solution of spherical triangles in crystallography. It has been adapted for seismological use by numbering the scales appropriately.

DESCRIPTION OF THE CHART

The chart consists of a stereographic projection of a hemisphere, on which the meridians and parallels have been drawn at intervals of two degrees. The meridians are numbered in both directions across the equator. In referring to points in the eastern hemisphere, the zero meridian is taken to be the left-hand half of the bounding circle of the projection, and the longitudes are the positive numbers reading from left to right. For the western hemisphere, the zero meridian is the right-hand boundary, and the longitudes are the negative numbers reading from right to left. The latitude corresponding to each parallel is entered on the bounding circle, and the angular distances of the parallels from the south pole are marked along the vertical axis. When in use, the chart is fixed to a smooth board, and covered by a sheet of tracing paper held in place by a single pin through the centre.

To find the distance and azimuth of a point P (whose latitude and longitude are φ', λ') from Q (φ, λ) first subtract the angle λ from the longitudes of both points. Plot P on the tracing paper at φ', $(\lambda' - \lambda)$ and Q at φ, O, using the sign convention for longitude outlined in the preceding paragraph, see (Figure 1). Now rotate the tracing paper until Q is carried to the south pole of the projection, and let P_1 and Q_1 be the displaced positions of P and Q. Then the distance PQ being equal to P_1Q_1 can be read immediately on the vertical scale of the projection. The azimuth of P is equal to the longitude of P_1, and is read on the equatorial scale of the projection.

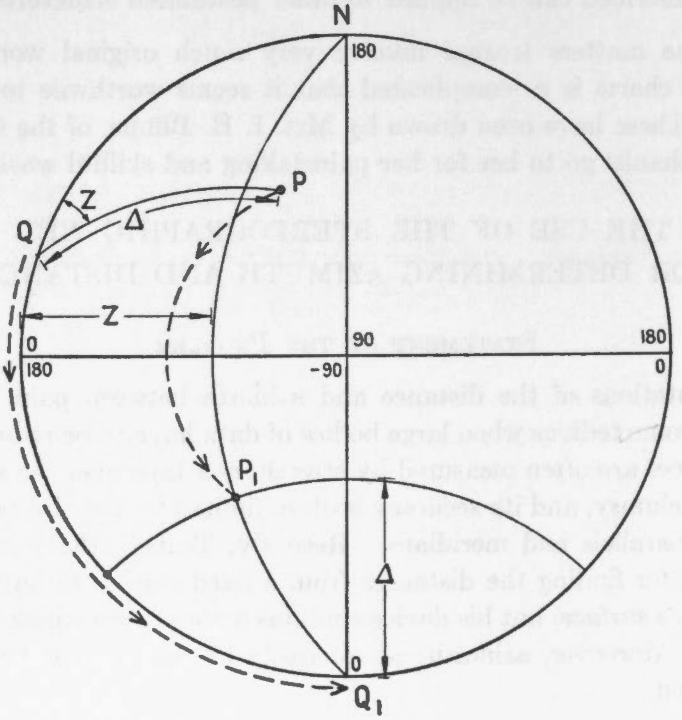
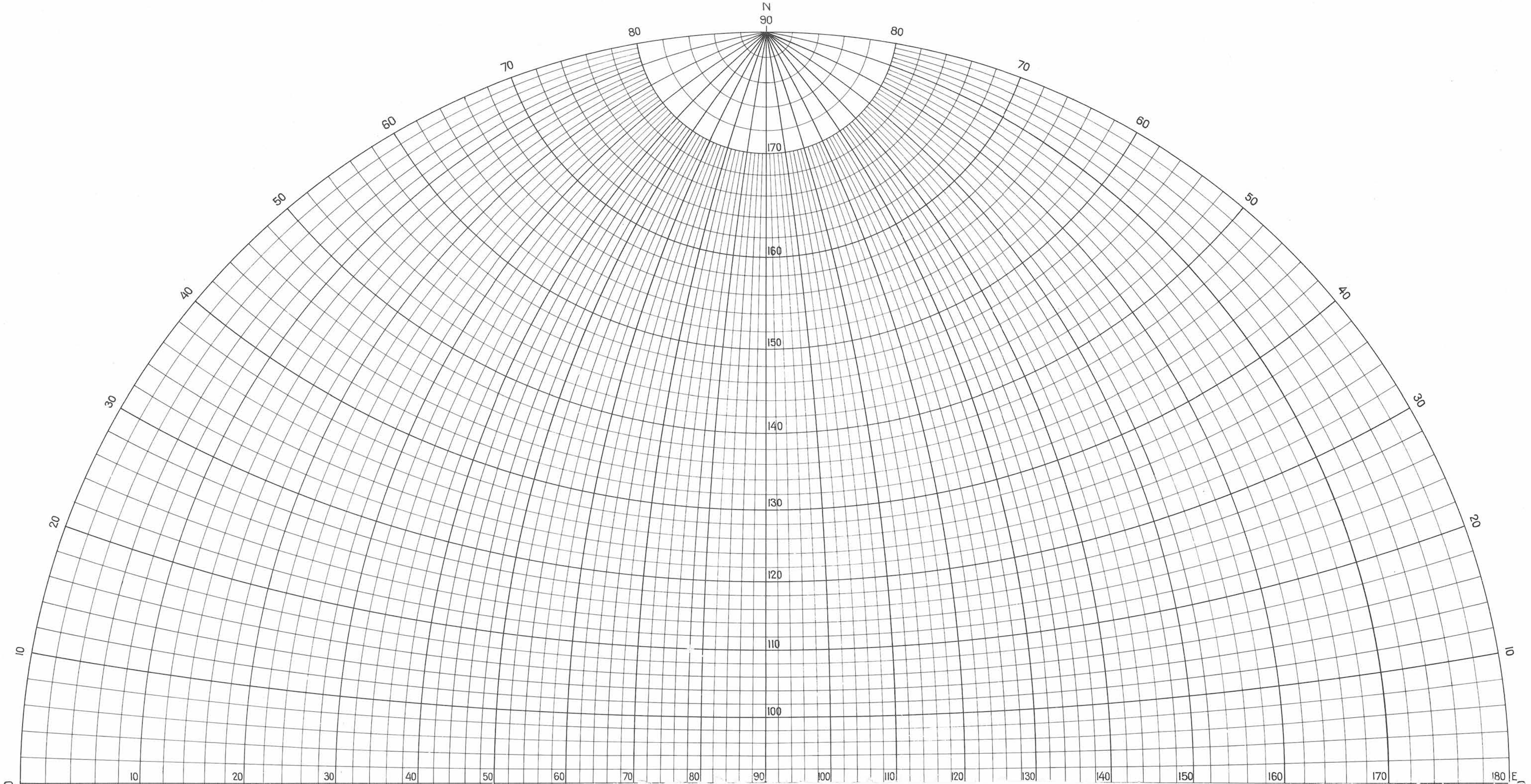
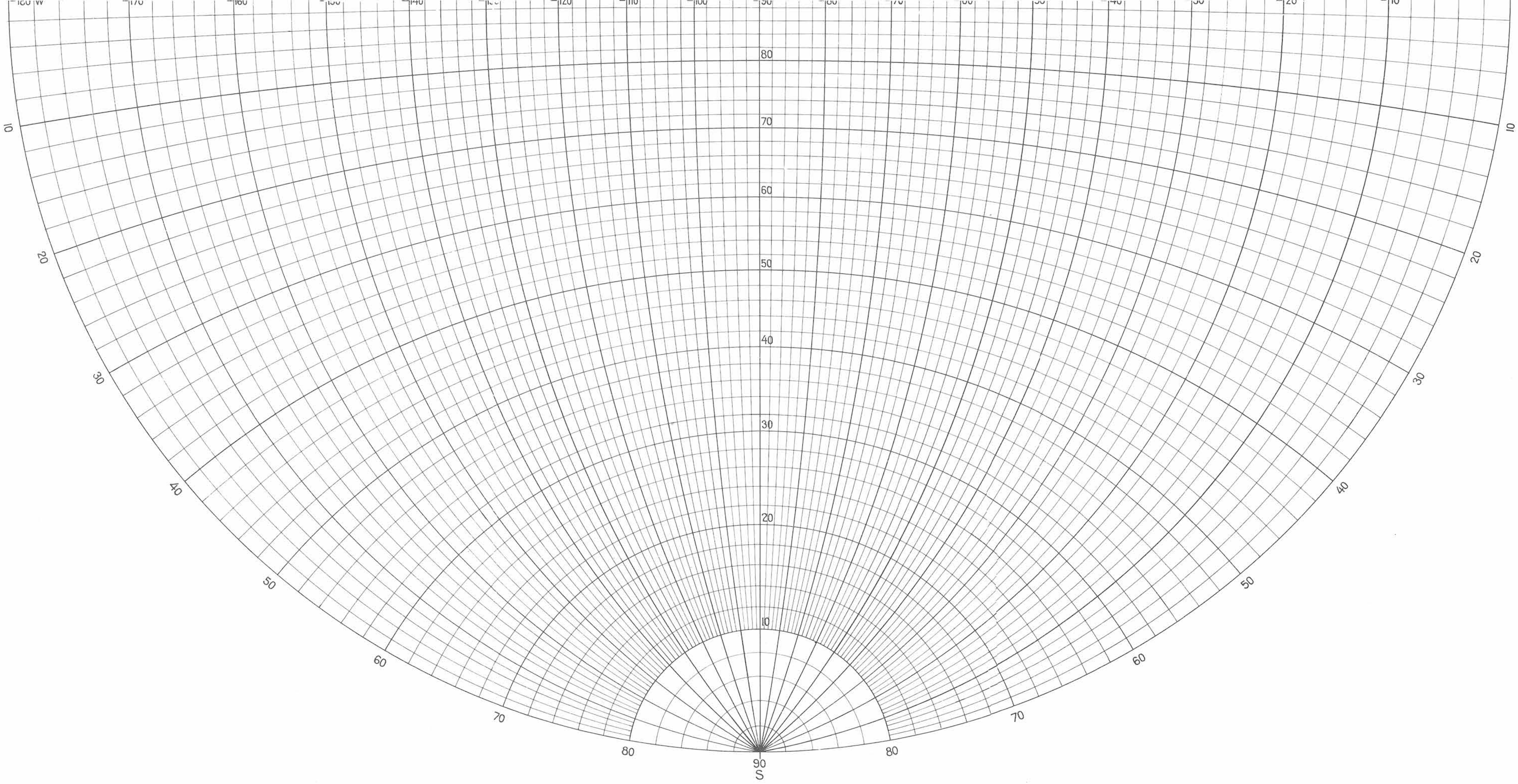


FIGURE 1


N
90
80
70
60
50
40
30
20
10
80
70
60
50
40
30
20
10
170
160
150
140
130
120
110
100
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
E


180 W
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
80
70
60
50
40
30
20
10
10
20
30
40
50
60
70
80
10
20
30
40
50
60
70
80
90
S

In proof of this result, consider the operations to be the displacements of P and Q on the surface of a sphere, rather than on the projection. The subtraction of λ from each longitude rotates P and Q about the polar axis until Q falls on the zero meridian. The rotation of the tracing paper rotates P and Q about the axis of projection, so that Q travels down the meridian QN. As neither rotation affects the distance between the two points P_1Q_1 is evidently equal to the original value of Δ. Moreover, the azimuth of P relative to Q is by definition the angle between the great circle PQ and the meridian QN. This is unaltered by the first rotation, but the second rotation transforms the great circle QP into the meridian Q_1P_1. The transformation of the azimuth of P into the longitude of P_1 follows immediately from this fact. The rotation of the tracing paper legitimately represents rotation on the sphere because of the symmetry about the projection axis. The choice of the stereographic projection in preference to others which have the necessary symmetry is made partly because it is the easiest to construct, and partly because it enables an entire hemisphere to be reproduced without excessive distortion.

Discussion of Errors

Despite the care with which the chart has been drawn, some inaccuracies must certainly exist within it. In addition to these, errors can arise from any misplacement of the pin which locates the centre of rotation of the tracing paper, and from the inability of the observer to interpolate exactly between the 2° lines. The effect of the eccentricity of the pin and of some of the other sources of error will be most marked when the tracing paper is turned through a large angle after the points are entered and before their positions are read. For this reason, more accurate readings may be expected when the epicentre is near the south pole than when it is farther north.

In order to determine the magnitudes of both the random and systematic terms, an observer was asked to determine the azimuth and distance from an epicentre in each of the northern and southern hemispheres to 20 recording stations. The stations were selected to be distributed as uniformly as possible over the earth. In order to reverse the effect of the observer's personal error the chart was used in its normal position for half of the test, and was inverted for the remainder. The readings were compared with computed values given to 0°.1. The mean error in degrees, and the standard deviation σ of a single observation under each of the four sets of conditions is given in Table I.

TABLE I

	Northern Epicentre	Southern Epicentre
Chart in normal position	Mean $\Delta_{\text{obs.}} - \Delta_{\text{calc.}} = -0{\cdot}03 \pm 0{\cdot}05$ $\sigma = 0{\cdot}16$	Mean $\Delta_{\text{obs.}} - \Delta_{\text{calc.}} = +0{\cdot}02 \pm 0{\cdot}04$ $\sigma = 0{\cdot}12$
	Mean $Z_{\text{obs.}} - Z_{\text{calc.}} = +0{\cdot}08 \pm 0{\cdot}06$ $\sigma = 0{\cdot}20$	Mean $Z_{\text{obs.}} - Z_{\text{calc.}} = -0{\cdot}02 \pm 0{\cdot}09$ $\sigma = 0{\cdot}28$
Chart Inverted	Mean $\Delta_{\text{obs.}} - \Delta_{\text{calc.}} = -0{\cdot}19 \pm {\cdot}07$ $\sigma = 0{\cdot}22$	Mean $\Delta_{\text{obs.}} - \Delta_{\text{calc.}} = -0{\cdot}06 \pm 0{\cdot}05$ $\sigma = 0{\cdot}14$
	Mean $Z_{\text{obs.}} - Z_{\text{calc.}} = +0{\cdot}06 \pm 0{\cdot}07$ $\sigma = 0{\cdot}23$	Mean $Z_{\text{obs.}} - Z_{\text{calc.}} = 0{\cdot}00 \pm 0{\cdot}06$ $\sigma = 0{\cdot}20$

As expected, there is some tendency for the largest systematic errors to occur in the readings which refer to the northern epicentre, but the systematic terms are not large compared with their standard deviations. A much larger statistical test would therefore be necessary to separate the sources of error, but it is clear that they are of the same order as those which are inherent in good epicentral determinations.

The same operator made a further 36 observations on a northern epicentre with different stations and a different copy of the chart. In this case the mean error for one observation of distance was 0°·16 ± 0°·13 and the corresponding error in azimuth was 0°·15 ± 0°·22. Of all the 116 observations only 6 were in error 0°·5 or more, and the largest error was 0°·6. These figures are consistent with the standard deviations given and further illustrate that the chart is sufficiently accurate for most purposes.

THE TRACING OF RAYS THROUGH THE EARTH

Derivation of the Chart

It is frequently useful to trace rays through the earth and so to obtain some idea of their depth of penetration and of their point of emergence. As an example, one of us (Hodgson and Allen, 1954) recently had reason to suspect that a complicated cusp was associated with the phase pP. The method to be described permitted the very rapid verification of this fact. An analytical demonstration has since been given by Bullen (1955).

It is well known that the path of a ray in a spherically stratified earth is governed by the equation

$$p = \frac{r}{v} \sin i \,, \tag{1}$$

where v is the velocity of propagation at a distance r from the centre and i the angle between the radius vector and the ray. The parameter p is a constant for the ray, defined by the values of r, v and i at any point upon it. Given the relationship between v and r, a ray of given p can be traced a step at a time. The process is tedious in the general case. If, however, the relationship between v and r can be expressed in a suitable algebraic form, it may be possible to derive an equation for the ray which will eliminate the labour of the step-by-step computation.

A particular case is that in which v and r are connected by an equation of the form

$$v = a - br^2. \tag{2}$$

Under these circumstances the ray paths are circles of radii

$$\rho = \frac{1}{2pb} . \tag{3}$$

Equation (2) does not apply to the whole of the real earth. For any assumed velocity distribution however the earth may be divided into zones in each of which an equation of the given form will apply. The velocity values derived by Jeffreys (1939) from the Jeffreys-Bullen travel-time curves (1940), have been used in the present study. In Figure 2 those velocities are plotted as a function of r^2 and a series of straight lines have been fitted to the points. The intersections of these lines define the boundaries of zones

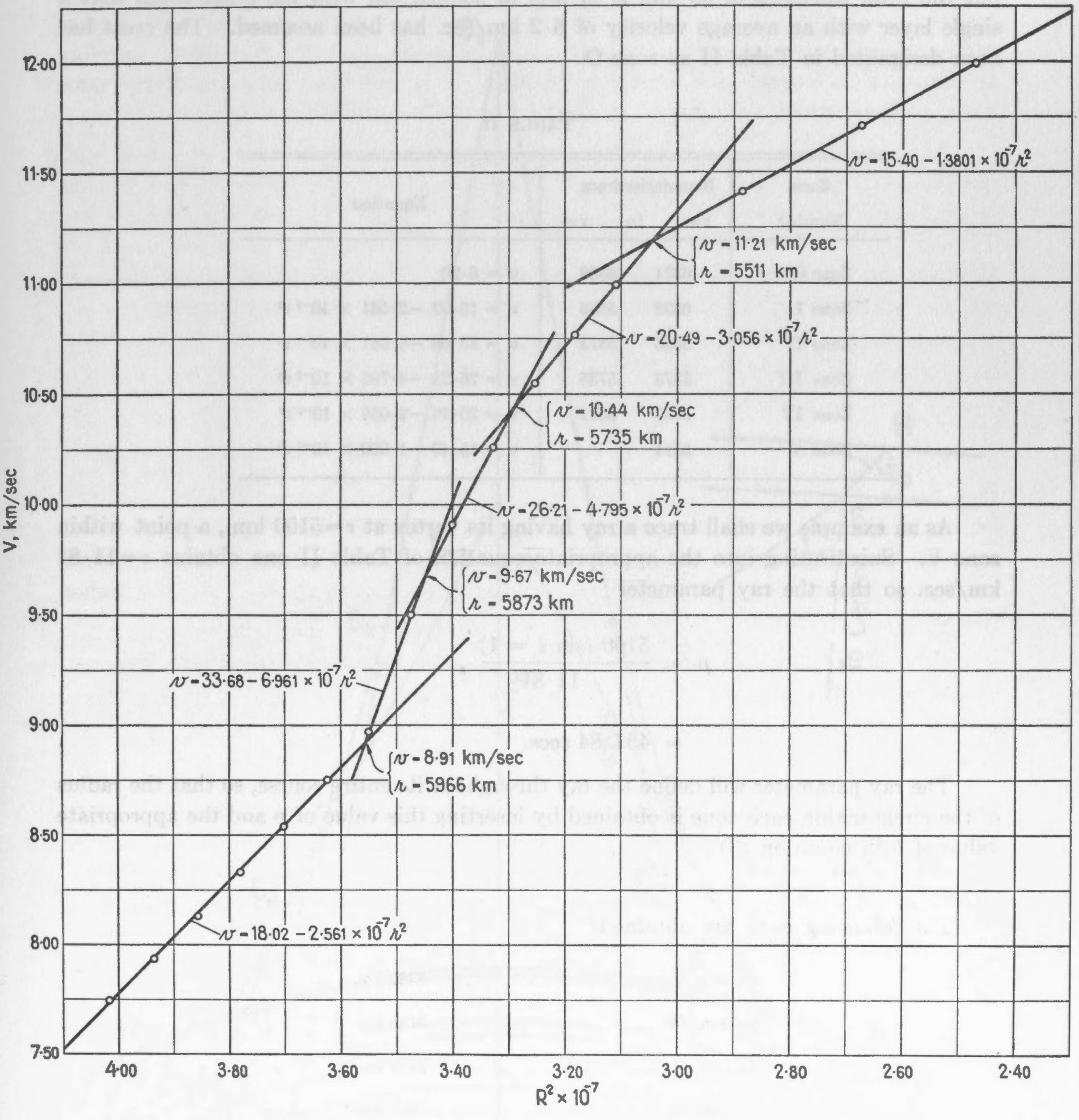


FIGURE 2

within which equations of the form (2) are assumed to hold. The equations appropriate to each zone are indicated on the diagram and are summarized in Table II. It should be stressed that the zone boundaries represent the intersections of lines chosen for convenience, and do not necessarily correspond to discontinuities in the earth. Figure 2 does not include any points relating to the crust. The Jeffreys-Bullen tables indicate two crustal layers, but the total thickness of 33 km. is so thin in comparison with the other zones that a single layer with an average velocity of 6·2 km/sec. has been assumed. The crust has been designated in Table II as zone O.

TABLE II

Zone Number	Boundaries from r=	to r=	Equation
Zone O	6371	6338	$v = 6{\cdot}20$
Zone I	6338	5966	$v = 18{\cdot}02 - 2{\cdot}561 \times 10^{-7} r^2$
Zone II	5966	5873	$v = 33{\cdot}68 - 6{\cdot}961 \times 10^{-7} r^2$
Zone III	5873	5735	$v = 26{\cdot}21 - 4{\cdot}795 \times 10^{-7} r^2$
Zone IV	5735	5511	$v = 20{\cdot}49 - 3{\cdot}056 \times 10^{-7} r^2$
Zone V	5511		$v = 15{\cdot}40 - 1{\cdot}380 \times 10^{-7} r^2$

As an example we shall trace a ray having its vertex at $r = 5100$ km., a point within zone V. Substituting into the appropriate equation of Table II one obtains $v = 11{\cdot}81$ km/sec. so that the ray parameter

$$p = \frac{5100\ (\sin i = 1)}{11{\cdot}81},$$

$$= 431{\cdot}84 \text{ secs.}$$

The ray parameter will define the ray throughout its entire course, so that the radius of the circle within each zone is obtained by inserting this value of p and the appropriate value of b in equation (3).

The following radii are obtained:

for zone V	8389 km.
for zone IV	3789 km.
for zone III	2415 km.
for zone II	1663 km.
for zone I	4521 km.

The use of these radii will become clear upon examination of Figure 3, in which the surface of the earth and the boundaries of the several zones have been drawn. The point A represents the vertex of the ray at a point $r = 5100$ km. Within zone V the ray is a circle of radius 8389 km. This circle may be drawn immediately with centre C_1 to intersect the boundary between zones IV and V at the points B, B.

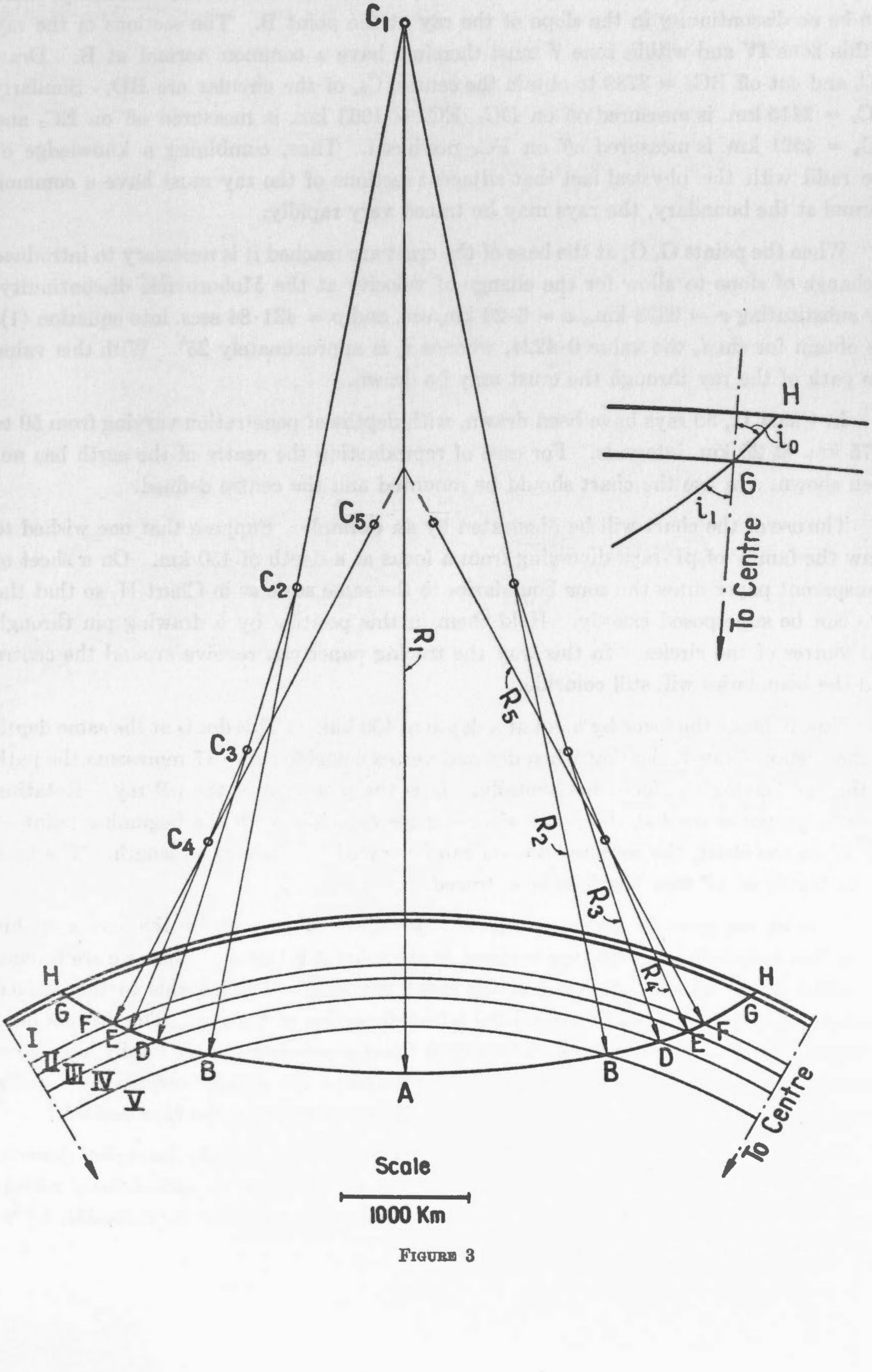

C1
C5
C2
C3
C4
R1
R5
R2
R3
R4
H
G
i0
i1
To Centre
H
G
F
E
D
B
A
B
D
E
F
G
H
I
II
III
IV
V
To Centre
Scale
1000 Km

FIGURE 3

Since the propagation velocity is the same on both sides of the zone boundary, there can be no discontinuity in the slope of the ray at the point B. The sections of the ray within zone IV and within zone V must therefore have a common normal at B. Draw BC_1 and cut off $BC_2 = 3789$ to obtain the centre, C_2, of the circular arc BD. Similarly $DC_3 = 2415$ km. is measured off on DC_2, $EC_4 = 1663$ km. is measured off on EC_3 and $FC_5 = 4521$ km. is measured off on FC_4 produced. Thus, combining a knowledge of the radii with the physical fact that adjacent sections of the ray must have a common normal at the boundary, the rays may be traced very rapidly.

When the points G, G, at the base of the crust are reached it is necessary to introduce a change of slope to allow for the change of velocity at the Mohorovičić discontinuity. By substituting $r = 6338$ km., $v = 6{\cdot}20$ km/sec. and $p = 431{\cdot}84$ secs. into equation (1), we obtain for sin i_0 the value 0·4224, whence i_0 is approximately 25°. With this value the path of the ray through the crust may be drawn.

In Chart II, 50 rays have been drawn, with depths of penetration varying from 50 to 1275 km. at 25 km. intervals. For ease of reproduction the centre of the earth has not been shown. In use the chart should be mounted and the centre defined.

The use of the chart will be illustrated by an example. Suppose that one wished to draw the family of pP rays diverging from a focus at a depth of 450 km. On a sheet of transparent paper draw the zone boundaries to the same scale as in Chart II, so that the two can be superposed exactly. Hold them in this position by a drawing pin through the centres of the circles. In this way the tracing paper can revolve around the centre and the boundaries will still coincide.

Now indicate the focus by a dot at a depth of 450 km. This dot is at the same depth as the vertex of ray 17, so that when dot and vertex coincide curve 17 represents the path of the ray leaving the focus horizontally. It is the p section of the pP ray. Rotating the tracing paper so that the point of emergence coincides with the beginning point of ray 17 on the chart, the reflected section can be traced throughout its length. The first of the family of pP rays has thus been traced.

Next let the focus be placed on ray 18. It will be slightly above the vertex of this ray so that in one direction the ray is rising, in the other it is falling. Since we are tracing the paths of pP we are interested in the rising ray only. Tracing this to the surface again swing the tracing paper to give the reflected section of the ray. The process may be repeated for rays of all higher numbers until the characteristics of the family have been determined. The cusps and other interesting features are usually defined by tracing every third or fourth ray, but an initial trial is necessary to select the rays desired.

In producing a drawing it is expected that the rays will normally be copied directly from the chart by means of a french curve. For those who wish to work directly with a compass the radii of the arcs and the values of the angle i_0 are given in Table III. The terms used in Table III are defined in Figure 3.

0° 1° 2° 3° 4° 5° 6° 7° 8° 9° 10° 11° 12° 13° 14° 15° 16° 17° 18° 19° 20° 21° 22° 23° 24° 25° 26° 27° 28° 29° 30° 31° 32° 33° 34° 35° 36° 37° 38° 39° 40° 41° 42° 43° 44° 45° 46° 47° 48° 49° 50° 51° 52°
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50
TO CENTRE
TO CENTRE
SCALE
KM 100 50 0 100 200 300 400 500 600 700 800 900 1000 KM

TABLE III

RADII OF THE CIRCULAR ARCS

(See Figure 3 for definition of terms)

Ray Number	Depth at Vertex	i_0 ° ′	R_5 km.	R_4 km.	R_3 km.	R_2 km.	R_1 km.
1	50	52 : 32	2406	—	—	—	—
2	75	51 : 29	2440	—	—	—	—
3	100	50 : 30	2475	—	—	—	—
4	125	49 : 32	2510	—	—	—	—
5	150	48 : 37	2545	—	—	—	—
6	175	47 : 44	2581	—	—	—	—
7	200	46 : 53	2616	—	—	—	—
8	225	46 : 04	2653	—	—	—	—
9	250	45 : 20	2686	—	—	—	—
10	275	44 : 33	2722	—	—	—	—
11	300	43 : 48	2759	—	—	—	—
12	325	43 : 04	2796	—	—	—	—
13	350	42 : 22	2834	—	—	—	—
14	375	41 : 44	2869	—	—	—	—
15	400	41 : 04	2907	—	—	—	—
16	425	39 : 53	2978	1096	—	—	—
17	450	38 : 37	3060	1126	—	—	—
18	475	37 : 28	3139	1155	—	—	—
19	500	36 : 21	3222	1186	—	—	—
20	525	35 : 37	3280	1207	1751	—	—
21	550	34 : 52	3341	1229	1784	—	—
22	575	34 : 09	3402	1252	1817	—	—
23	600	33 : 27	3464	1275	1850	—	—
24	625	32 : 47	3526	1298	1884	—	—
25	650	32 : 14	3580	1317	1912	3000	—
26	675	31 : 47	3626	1334	1937	3039	—
27	700	31 : 21	3670	1350	1960	3079	—
28	725	30 : 55	3717	1368	1985	3115	—
29	750	30 : 31	3762	1384	2009	3152	—
30	775	30 : 05	3810	1402	2035	3193	—
31	800	29 : 42	3855	1418	2059	3231	—
32	825	29 : 17	3904	1436	2085	3272	—
33	850	28 : 53	3954	1455	2112	3313	—
34	875	28 : 36	3989	1468	2131	3343	7403
35	900	28 : 21	4022	1480	2148	3370	7463
36	925	28 : 06	4055	1492	2166	3398	7524
37	950	27 : 53	4084	1503	2181	3423	7579
38	975	27 : 38	4117	1515	2199	3451	7641
39	1000	27 : 24	4151	1527	2217	3479	7704
40	1025	27 : 09	4185	1540	2235	3507	7766
41	1050	26 : 56	4216	1551	2252	3533	7824
42	1075	26 : 42	4251	1564	2270	3562	7888
43	1100	26 : 28	4286	1577	2289	3591	7952
44	1125	26 : 15	4317	1588	2306	3618	8011
45	1150	26 : 01	4353	1601	2325	3648	8078
46	1175	25 : 49	4385	1613	2342	3675	8137
47	1200	25 : 35	4421	1627	2361	3705	8204
48	1225	25 : 22	4460	1640	2381	3736	8272
49	1250	25 : 10	4491	1652	2399	3764	8334
50	1275	24 : 57	4529	1666	2419	3795	8403

Applications to some Problems

Figures 4 to 9 show some ray diagrams constructed with the aid of a chart similar to Chart II. They were actually drawn from an earlier model in which the rays were drawn with their vertex at even values of radius r rather than of even values of depth. The rays shown in these figures are therefore not identical with any of those shown in Chart II.

In Figure 4 the rays giving rise to the "20° cusp" on the P curve are traced. It is shown that the points of reversal are at something less than 22° and at about 19°, a little short of the 18°·5 given in the published tables. This is to be expected, since it would be a matter of accident if the ray corresponding to the exact end of the cusp were one of those available in Chart II. Figure 5 illustrates the cusp arrangement for pP rays originating at focal depth of 0·02R. It will be noted that there are two cusps, an initial one between 20° and 19° due to ray geometry, and a second analagous to the "20° cusp". In Figures 6 to 9 the interaction of these two cusps with increasing focal depth has been illustrated. These figures will supplement the theoretical discussion given by Bullen (1955).

CONCLUSION

To be of value the charts described in this paper should be mounted with a minimum of distortion. An extra supply of the charts has been printed, and copies will be mailed unfolded to anyone wishing them. Requests should be addressed to the authors.

References

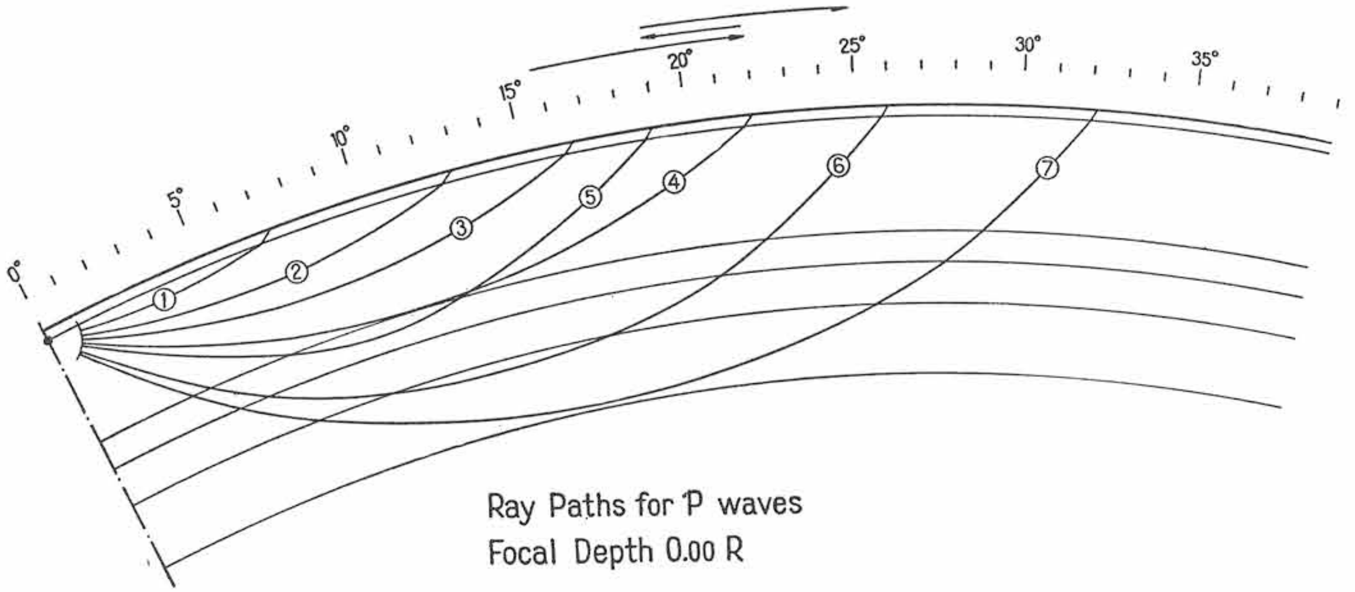
Bullen, K. E.
1955 "Features of Seismic pP and PP Rays", M.N.R.A.S., Geoph. Suppl., in press.

Hodgson, J. H. and Allen, J. F. J.
1954 "Tables of Extended Distances for PP and pP", *Publications of the Dominion Observatory*, 16, 351-362

Jeffreys, H.
1939 "Times of P, S and SKS, and Velocities of P and S", M.N.R.A.S., Geoph. Suppl., 4, 498-533.

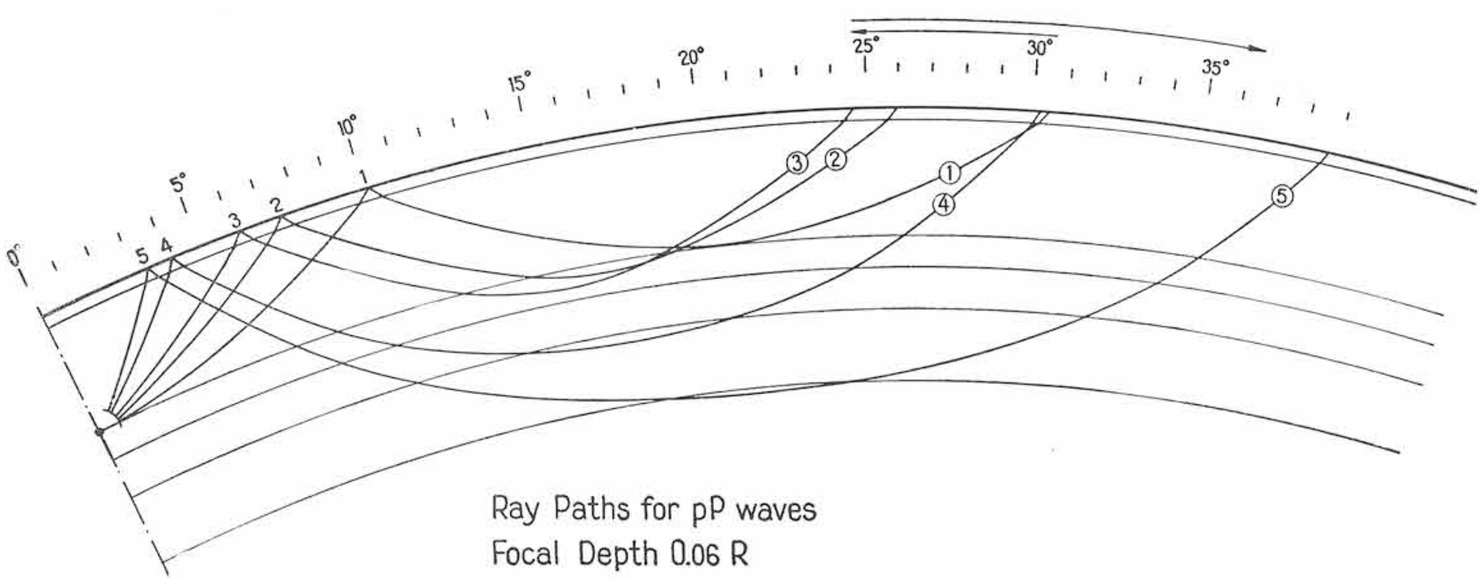
Jeffreys, H., and Bullen, K. E.
1940 "*Seismological Tables*", British Association for the Advancement of Science.

Tsuboi, C.
1951 "A Simple Instrument Useful for Finding the Angular Distance of a Point (φ, λ) from a Fixed Point (φ_o, λ_o) on the Earth's Surface", *Geophysical Notes, Tokyo University*, 4, No. 4.



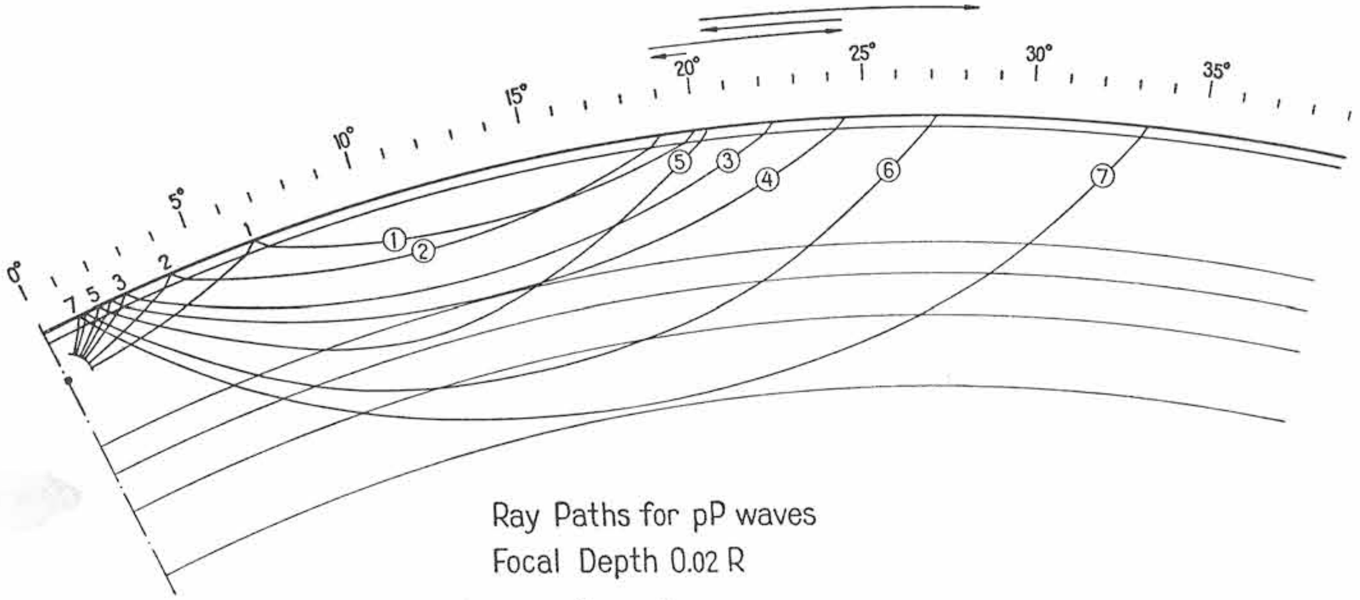
Ray Paths for P waves
Focal Depth 0.00 R

FIGURE 4



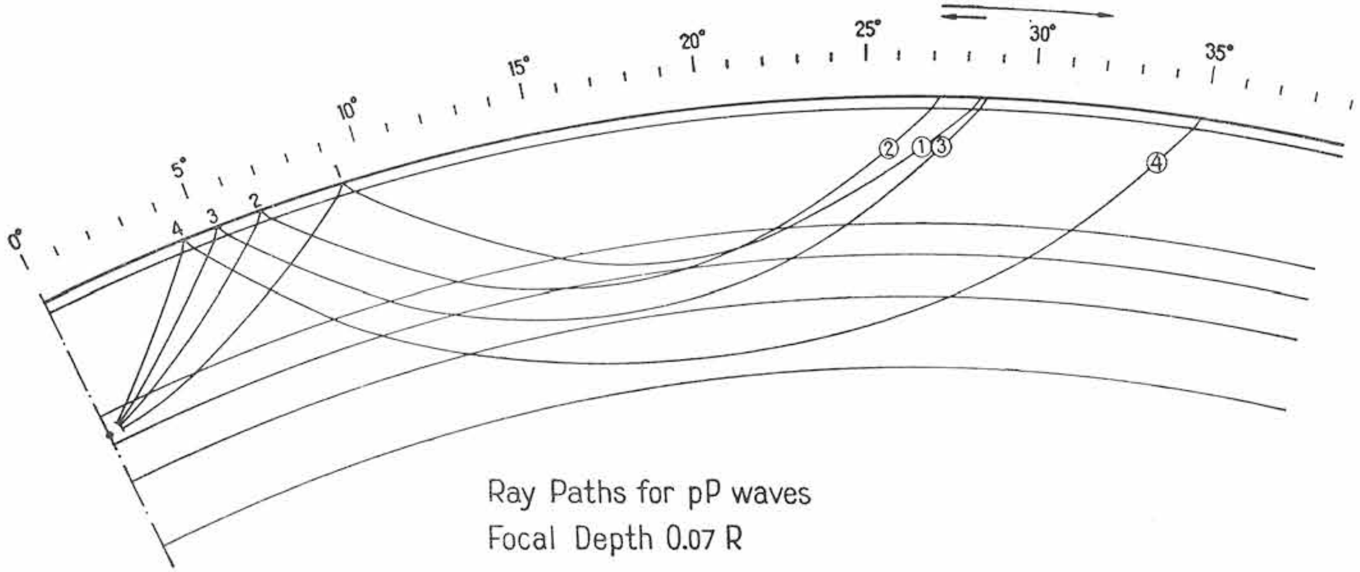
Ray Paths for pP waves
Focal Depth 0.06 R

FIGURE 7



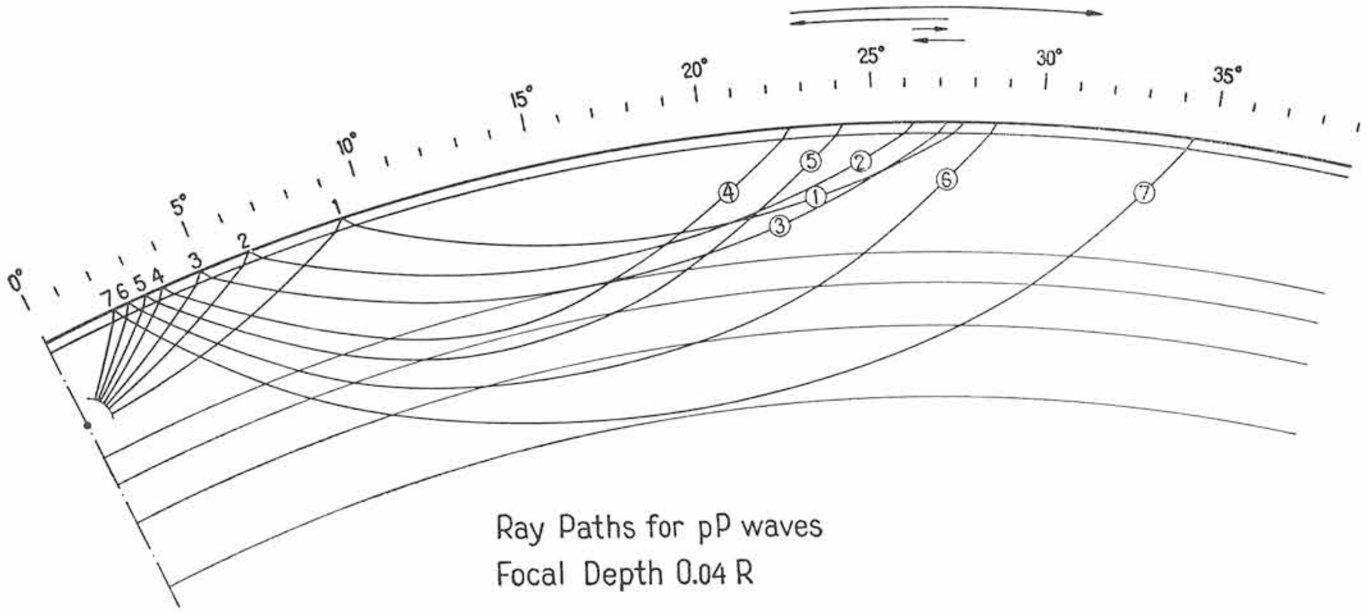
Ray Paths for pP waves
Focal Depth 0.02 R

FIGURE 5



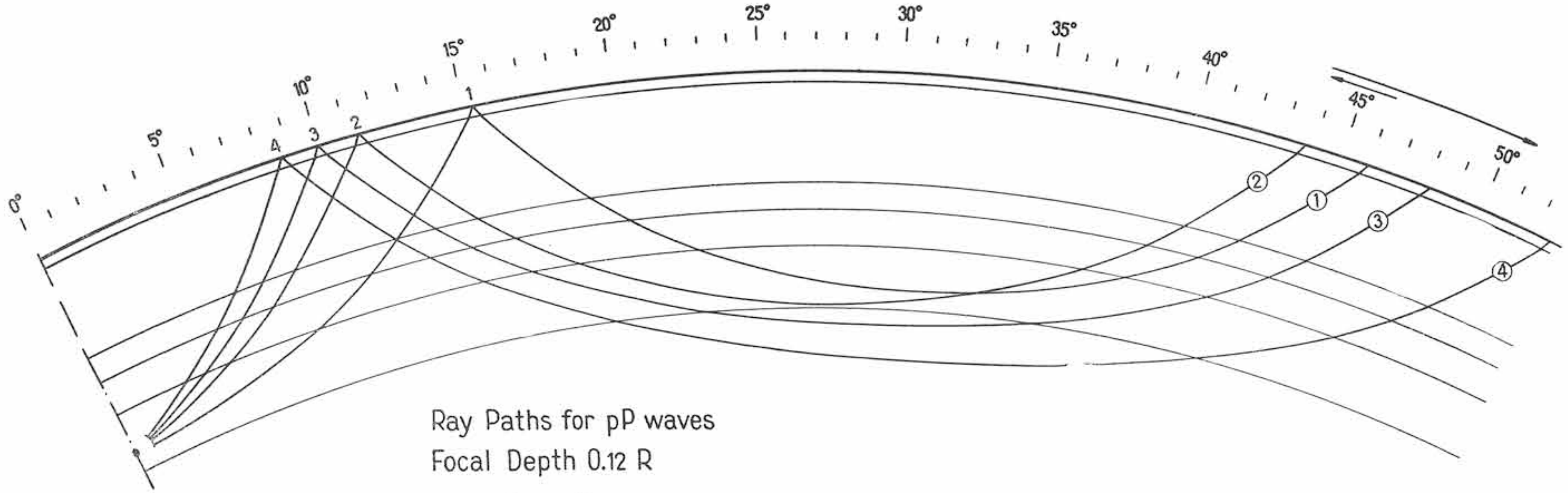
Ray Paths for pP waves
Focal Depth 0.07 R

FIGURE 8



Ray Paths for pP waves
Focal Depth 0.04 R

FIGURE 6



Ray Paths for pP waves
Focal Depth 0.12 R

FIGURE 9