

CANADA  
DEPARTMENT OF MINES AND TECHNICAL SURVEYS  
DOMINION OBSERVATORIES

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PUBLICATIONS  
OF THE  
**Dominion Observatory**

VOLUME XIX No. 1

GRAVITY MEASUREMENTS IN CANADA  
JANUARY 1, 1954 TO DECEMBER 31, 1956

BY  
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Report of the  
International Association of Geodesy  
Eleventh General Assembly  
International Union of Geodesy & Geophysics  
Toronto 1957

EDMOND CLOUTIER, C.M.G., O.A., D.S.P.  
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY  
OTTAWA, 1957

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## INTRODUCTION

In accordance with the request of the International Union of Geodesy and Geophysics, this report is intended to cover gravity investigations in Canada during the period from 1st January 1954, to 31st December 1956. Earlier gravity work in Canada has been presented in previous reports, one to the International Gravimetric Commission, Paris, September 1953, and General Report No. 6 presented to the General Assembly of the I.U.G.G., Rome, 1954(1). The organizations that have made gravity studies in Canada during the last three years and whose work will be discussed, are the Dominion Observatory, the National Research Council of Canada, the Nova Scotia Research Foundation, and the Universities of Alberta, Toronto and Western Ontario.

The Dominion Observatory is charged with the responsibility of mapping the gravity field within Canada and throughout her coastal waters for application to problems of geodesy and for crustal studies. In addition to its regular program of extending the regional coverage special emphasis has been placed on problems to improve the homogeneity of the Canadian network and to strengthen gravity ties with the world network. In particular, attention has been given to: (i) the establishment of a well-connected system of gravity reference stations throughout Canada; (ii) the establishment of a gravity standard in eastern Canada and the United States suitable for the comparison and calibration of gravimeters; (iii) the improvement of gravity ties between the fundamental gravity station in Ottawa and other national reference stations; (iv) instrumental research directed toward the design and improvement of gravity measuring devices, for both land and sea operation.

The National Research Council of Canada has been chiefly concerned with the experiment started several years ago to determine the absolute value of gravity at Ottawa but, as in previous years, has indirectly contributed to other gravity investigations by means of research grants to Universities.

During the period under review the universities have made increased use of gravity data in structural studies of the crust. The University of Toronto has continued its investigations in southern Ontario; the University of Alberta in 1955 announced its intention of making gravity studies throughout the foothills and mountains of Alberta; and in 1956, the University of Western Ontario began a study of the structural implications of the gravity anomalies for the Gaspé region of Quebec.

Important gravity investigations have also been carried out by the Nova Scotia Research Foundation over certain sedimentary areas in Nova Scotia.

The progress that has been made by these various organizations in advancing the different phases of their investigations will be indicated in the following report and on the accompanying maps.

## ABSOLUTE MEASUREMENTS

The absolute determination of the acceleration due to gravity is being carried out in the laboratories of the National Research Council in Ottawa by the free-fall method. In the preliminary experiments, a stainless steel bar, 2 meters in length and having 7 metallized glass scales, was dropped. The scales were so spaced along the bar, that each in turn was photographed as it fell past the axis of a fixed camera in synchronization with the flashes of a spark-gap light-source, activated at precisely 10 cycles per second. The final experiment will involve an invar bar geometrically similar to the stainless steel, but having only 3 scales, each of sufficient length to permit several independent determinations of  $g$ .

The Ottawa experiment is nearing completion and the final result is awaited with great interest. Since it was first started in 1950 considerable impetus has been given to the problem of absolute measurements by other scientific groups throughout the world. At the Tenth General Assembly of the International Union of Geodesy and Geophysics, Rome, 1954, no less than nine such experiments were reported (2) to be in progress. Since that time several other interested countries have announced their intentions to carry out similar experiments. To facilitate comparisons of the final Ottawa result with other absolute determinations the reference base of the absolute gravity apparatus at the National Research Laboratories has been accurately connected by gravimeters to the first order world network with the following result:

From OTTAWA (Absolute Station)  
To OTTAWA (National Reference Station)  
 $\Delta g = -7.29 \pm 0.03$  mgals.

## CALIBRATION STANDARDS FOR GRAVIMETERS

The establishment of a line of precise pendulum stations over the latitude range of North America for the purpose of providing a uniform standard for the calibration of gravimeters used for geodetic purposes, has received the attention of both Canadian and American scientists in the last few years. During 1952 and 1953 pendulums on loan from the University of Cambridge were used for measurements at sixteen points between Mexico City and Fairbanks, Alaska, the total range in gravity exceeding 4,000 milligals (3, 4). The measurements were repeated by the Wood's Hole Oceanographic Institution, and the University of Wisconsin, using quartz pendulums of the Gulf Oil Company. As preliminary values of the determinations with the Gulf apparatus are now available (5) a comparison of the two sets of data is now possible.

After adjusting the results to a common datum it is found that the root mean square difference between the sets of observations is very nearly one milligal. The two independent sets of gravity values have therefore been well determined and are probably more accurate than those of any other comparable group of pendulum measurements. There is, however, a possibility that they might be brought into even closer agreement. The Cambridge pendulum values for stations in Canada and Alaska are on the

average 1 milligal greater than the Gulf pendulum results for the same stations, while to the south the Cambridge values are about 0.8 milligals smaller. Since this grouping of stations corresponds to those observed in different seasons with the Cambridge apparatus, it is reasonable to suspect that these apparent systematic differences are related to errors in estimating sub-base values to which the yearly sets of measurements were referred. The systematic differences may in part reflect similar errors in the Gulf sub-base values.

A re-examination of the observed periods of the Cambridge pendulums for this line of stations (6) strengthens this hypothesis and shows also that one pendulum was much more stable than the other pendulums used. Moreover it has been reported (7) that on return of the Cambridge apparatus to England, one set of agate flats on which the pendulums swing had become loose, giving rise to an erratic behaviour of any pendulum swung on it. The magnitude of the errors resulting from such a condition may not have been appreciable, but in view of the importance of this line of pendulum stations it is considered that further observations should be carried out before any attempt be made to adopt definitive values. Present plans of the Dominion Observatory include the re-occupation of a selected number of sites along the line with the Observatory's newly constructed two-pendulum apparatus during the summer of 1957. A looping program with several gravimeters, carefully executed over the full length of the line, would also do much to eliminate the present uncertainties.

The Canadian portion of the North American Calibration Line is the standard provisionally adopted for the adjustment of all regional gravity data in Canada. Calibrations of gravimeters based upon this standard agree within about 4 parts in  $10^4$  with calibrations determined by least squares against regionally distributed stations observed with Mendenhall pendulums(8).

Two other base lines used for calibration of gravimeters in Canada are illustrated in Figure 1. The central Canada line between Winnipeg, Churchill, and Resolute Bay permits a calibration over a range of 1,900 milligals. This line has not been used for such purposes in recent years since base station values at Churchill and Resolute Bay were determined with the Mendenhall apparatus under rather unfavourable conditions and are subject to large uncertainties. It may be of interest, however, that first class pendulum observations are planned for these and other high latitude stations in Canada during the International Geophysical Year.\*

A well-established series of stations on a north-south line passing through Ottawa (9) forms a third calibration line which provides a convenient standard for frequent and regular comparison. Although originally of short range, the line has been extended south to Washington, D.C., and north to Senneterre, Quebec, so that its present overall range is nearly 700 milligals. Values of gravity tentatively adopted for stations on this line depend upon calibrations against Cambridge pendulum values over the Canadian portion of the North American Calibration line, as do those of the primary gravimeter network of Canada.

\* See "Proposed Canadian Program for International Geophysical Year 1956" Associate Committee on Geodesy and Geophysics, National Research Council, Ottawa.



Fig. 1. Gravimeter reference network and calibration base lines.

## INTERNATIONAL GRAVITY CONNECTIONS

*(a) Connections between Fundamental Gravity Stations in Ottawa, Teddington, and Washington*

On completion of the program to establish a line of precise pendulum stations from Mexico to Alaska in 1953, the Dominion Observatory in cooperation with the National Physical Laboratory, Teddington, used the Cambridge apparatus to make comparisons between the fundamental gravity stations of Canada, the United States and Great Britain (10). Assuming a value on the Potsdam system of 981.1963 for the British fundamental station at Teddington, the measured differences lead to the following values for the national reference stations of Canada and the United States:

OTTAWA.....	980.6191 cm/sec <sup>2</sup>
(National Reference Station)	
WASHINGTON.....	980.1192 cm/sec <sup>2</sup> .
(Commerce Building)	

The value deduced for Ottawa is 2.9 milligals smaller than the adopted value for this station which was obtained by direct comparison with Potsdam (11) using Mendenhall pendulums. Since the presently measured Teddington-Washington difference is in excellent agreement with a previous determination (12) observed with the same Cambridge pendulums, it was decided to check the Ottawa-Washington difference by measurements with gravimeters calibrated against the Canadian standard previously described.

Detailed looping procedures were carried out and observations made with three gravimeters at some twenty-five stations to extend the existing Ottawa base line (*see* previous section) to Washington, D.C. Nine independent sets of measurements between Ottawa and Washington gave differences in gravity consistent within one-tenth of a milligal. The mean difference is 1.7 milligals greater than was obtained by measurement with the Cambridge pendulums and is 0.3 milligal less than the provisional values obtained with the Gulf quartz pendulum apparatus (5). In the fall of 1956 the Dominion Observatory initiated a program to make a series of pendulum measurements along the Ottawa-Washington base line, which should do much to resolve the uncertainty of this important gravity connection.

*(b) Gravimeter Ties with the European System*

Observation with pendulums is usually the most satisfactory means of making accurate gravity ties between distant points. However, if the differences are small, gravimeters may be used with considerable success since the uncertainty of their calibrations will have no appreciable effect on the result. In 1955 a program using gravimeters was initiated to strengthen the ties between the North American and European gravity networks. In cooperation with the Geophysical Observatory in Trieste, Italy, an accurate tie was successfully completed between Gander airport, Newfoundland, and Orly Field, near Paris, France. The results of these measurements (13) combined with similar work previously carried out between New York and Rome (14) permitted a comparison to be made between gravity standards employed in Europe and North America. The

closure error is about 0.25 milligal and suggests that over a range of 700 milligals the European gravity standard and that employed by the Dominion Observatory agree to within 0.03 per cent. (The European gravity difference is the greater). This agreement appears to be highly satisfactory but for confirmation of these results a third inter-continental connection of high accuracy was completed in October, 1956, between Ottawa and Geneva, Switzerland.

These inter-continental comparisons depend entirely upon the gravity standards now in use by the Dominion Observatory. To ensure that these are similar to standards employed elsewhere in North America, the U.S. Coast and Geodetic Survey completed in October 1956, careful gravimeter measurements on the base line established by the Dominion Observatory between Ottawa and Washington. At the same time the Dominion Observatory made comparisons on the U.S. Coast and Geodetic Survey calibration line near Washington. The results of the complete investigation are being analyzed and will be reported elsewhere.

## NATIONAL GRAVITY NETWORK

### (a) *The Primary Gravimeter Network*

At the expense of increasing the gravity coverage of Canada special emphasis has been placed during the last few years in improving the ties within the primary gravimeter network and in extending this network to include the base stations of previous regional surveys. Both air and ground transportation have been employed and in all cases the successive stations forming the links of the primary network have been interconnected by two alternate observations at each end of the link. The length of each link has been chosen so that the travelling time between stations does not exceed one hour. The progress that has been achieved to the end of 1956 is illustrated in Figure 1.

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In 1955 one party using three gravimeters and aircraft transportation travelled about 30,000 miles to establish a system of primary stations at 48 principal airports throughout southern Canada. On the average these are about 150 miles apart, and form a series of six closed nets extending from Vancouver, B.C., to Gander, Newfoundland. Accurate ties were made to previous gravimeter networks and to sites where pendulum measurements had been made with the Mendenhall and/or Cambridge apparatus.

The results of the 1955 survey and previous base-looping programs are consistent and appear to be highly satisfactory. Systematic errors, usually due to uncertainties in the calibration constants of the gravimeters used, have been largely removed by regular and frequent comparisons over the Ottawa calibration line. Random errors are estimated to be less than  $\pm 0.3$  milligal and the network should provide, therefore, a suitable datum for control and adjustment of all regional surveys in southern Canada.

### (b) *Regional Measurements*

The status of regional gravity mapping of Canada is best summarized in Figure 2, which shows the areas for which data are now available. The measurements are principally those of the Dominion Observatory although contributions have been made through detailed surveys carried out as research projects by graduate students of the University

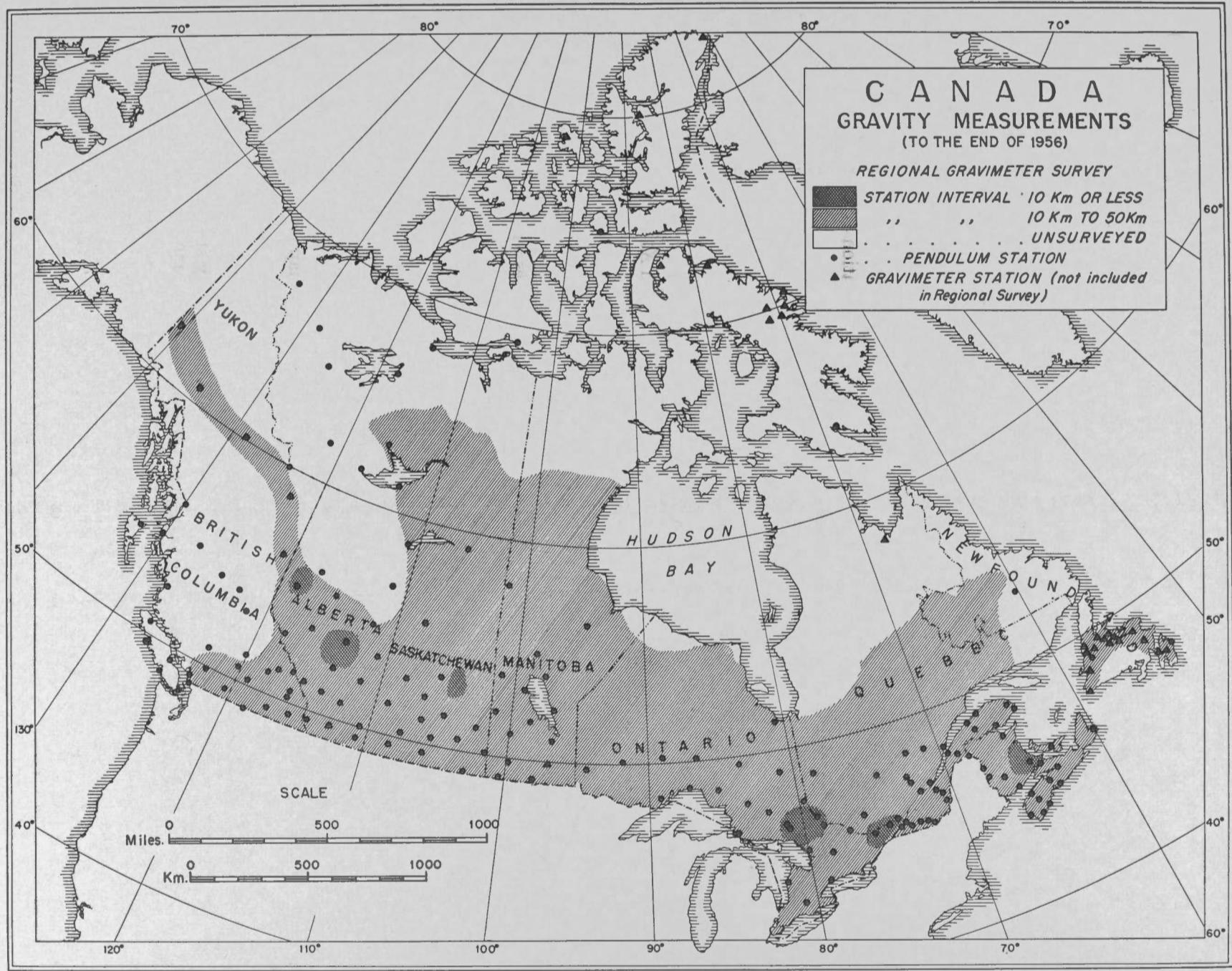


Fig. 2. Gravity measurements in Canada to the end of 1956.

of Toronto, Harvard University, and more recently the University of Alberta. Selected gravity data has also been released by several major oil companies to provide increased coverage of the prairie provinces in western Canada.

During the period under review the regional gravimeter network of Canada was extended to include 1,760 additional stations. This work may be briefly summarized as follows:

#### I. Measurements by the Dominion Observatory

- (i) In 1954 and 1956 survey parties using aircraft transportation established approximately 300 gravimeter stations at intervals of 10 to 15 miles throughout a wide area in north central Quebec. The region lies wholly within the Precambrian Shield.
- (ii) During the same field seasons other survey parties using automobile transportation increased the gravity coverage of southern Quebec with the establishment of nearly 700 new stations. About 500 of these were located in the Eastern Townships and Gaspé region, the remainder throughout the mining regions near Noranda and Senneterre.
- (iii) In 1954 approximately 500 stations were observed along highways and roads throughout the Cordilleran region of western Canada. The measurements are in sufficient detail to prepare a preliminary gravity map of the area.
- (iv) In conjunction with the establishment of primary control stations in 1955 more than 100 regional measurements were completed on highways north and west from Port Arthur in northwestern Ontario and in northwestern Alberta.

#### II. Measurements by the Universities

- (i) Nearly 200 gravity stations were established by the University of Alberta in 1956 with a Worden gravimeter in the Cold Lake area of northeastern Alberta and in the foothills of the Rocky Mountains in western Alberta.
- (ii) Important gravity studies of the gravitational field over a portion of the Grenville Sub-province of the Canadian Shield have been made by the University of Toronto. Six hundred and fifty stations were established in a strip 40 miles wide crossing the Ottawa valley in the vicinity of Calumet Island (15). Recently gravity surveys have been carried out in the Georgian Bay area and some measurements have been made over the ice of the Salmon glacier near the Alaska boundary of British Columbia.

Through the combined efforts of the organizations mentioned above more than 15,000 regional observations in Canada are now available for geodetic and regional studies. The greatest station density, as shown by the shaded portion of the map (Figure 2), is in the region south of latitude 60 degrees. To the north, only scattered pendulum and gravimeter stations have been observed, but it may be of interest to note that these extend over the whole latitude range of Canada. The most northerly gravity station is located at the Canadian weather station, Alert, in latitude 83 degrees, about 450 miles from the north pole.

*(c) Coordination and Documentation of Gravity Data*

The Dominion Observatory acts as the central organization in Canada for the collection and coordination of regional gravity data and for its subsequent submission to the International Gravimetric Bureau in Paris. With the exception of the measurements carried out by the Observatory in the maritime provinces (16, 17), by the University of Toronto in southern Ontario and the recent work of the University of Alberta, all regional gravity observations have been adjusted to the primary reference system described above. Documentation of data has kept pace with the regional measurements and with adjustments to the national datum. During the last three years all adjusted gravity data have been assembled in tables giving the principal facts for each station, namely, the geographical coordinates, the elevation, observed gravity, the Free Air and Bouguer anomalies. To facilitate analysis the data are arranged by degree squares of latitude and longitude (i.e. 1 degree latitude  $\times$  1 degree longitude). By December 31, 1956, the results for nearly 10,000 stations had been submitted to the International Gravimetric Bureau, Paris.

*(d) Contributions from Industry*

The release by commercial prospecting concerns and the petroleum industry of gravity data for geodetic and other scientific purposes has already been mentioned. However, during the past few years there has been increased activity in oil exploration in western Canada, with correspondingly broader gravity coverage. In 1955 a request by the Dominion Observatory for the release of more data met with favourable response. More recently the Canadian Society of Exploration Geophysicists, representing a large number of the practising geophysicists in Canada, offered to act as a liaison group between the oil industry and the National Committee for Canada on Geodesy and Geophysics. As part of a contribution to the Canadian program during the International Geophysical Year the C.S.E.G. hopes to stimulate the release of gravity data, selected to provide sufficient control for regional studies without revealing information of competitive interest.

To facilitate the adjustment of such gravity information to the national reference system, the Dominion Observatory initiated a gravimeter program in 1955 to increase the number of control stations throughout western Canada. This program is to be accelerated and plans are underway for two crews to carry out base-looping assignments throughout the prairie regions during the field seasons of 1957 and 1958.

## APPLICATION OF GRAVITY MEASUREMENTS

*(a) Structural Studies*

A number of studies of the gravity results and their geological implications have been completed for several regions in Canada. These investigations, as well as some dealing specifically with problems of exploration geophysics, are listed in the bibliography in a later section. A brief summary is presented here of the results of several regional studies that are now in progress or have recently been completed.

(i) *British Columbia*—An analysis of the gravity results of the 1954 survey throughout southern British Columbia has been completed. In the report (18) maps of Bouguer and isostatic anomaly for the region are presented and the compensation of the mountain

systems is discussed. An Airy form of compensation appears reasonable, although certain features such as granitic batholiths show considerable isostatic anomalies. Detailed measurements over the Rocky Mountain Trench indicate a considerable thickness of lighter fill in some sections, but suggest no major crustal dislocation beneath it.

(ii) *Alberta*—Gravimeter measurements have been carried out by the University of Alberta over an area of about 100 miles square near the edge of the Canadian Shield. A study is being carried out to determine if certain gravitational features observed in the foothills of the Rocky Mountains are due to the relief or to changes in the lithology of the Precambrian basement rocks.

(iii) *Saskatchewan*—Several gravity investigations have been carried out during the last few years over and in the vicinity of circular topographic features believed to have been formed by the impact and explosion of meteorites. Negative gravity fields associated with some features are believed to reflect disturbed bed-rock conditions and fracturing to great depths as a result of explosion. Deep Bay, whose waters form the southeastern part of Reindeer Lake in northern Saskatchewan, occupies a circular depression having a diameter about  $8\frac{1}{2}$  miles. Topographical, geological and geophysical evidence (19) are consistent with the hypothesis that Deep Bay was formed by explosion of a meteorite.

(iv) *Quebec*—The results of all gravity measurements in Quebec to the end of 1956 for an area south of latitude 52 degrees north and west of longitude 64 degrees west are given and analyzed in a report (20). The correlation of the Bouguer anomalies with major geological structures is discussed and it is suggested that the chief anomaly trends are caused by systematic differences in density. There appears to be no gravitational evidence along the northern boundary of the Grenville which could be related to the presence of the presumed Huron-Mistassini thrust fault. Large anorthosite bodies in the area are characterized by negative gravity anomalies, which together with the determinations of density show that these rocks are less dense than the surrounding granitic rocks. The positive anomalies in the Eastern Townships and Gaspé are believed to be associated with a belt of ultrabasic rock at moderate depth which surfaces in the Richmond-Thetford and Gaspé districts.

Gravity surveys in 1954, over an extended area to the northeast of the region considered in the report just summarized, disclosed a belt of intensely negative Bouguer and isostatic anomalies. The belt is nearly 140 miles wide and has been traced for about 300 miles from Lake Mistassini to Mount Wright near the southwestern tip of the 'Labrador trough'. Its axis trends northeast along the height of land and parallels the northern border of the Grenville geological province. An analysis of the gravity data shows (21) that the anomalies cannot be accounted for by isostatic compensation. Very steep gradients on the flanks of the gravity trough suggest that a near-surface mass deficiency must be one of the principal causes for the negative anomalies. Although relatively light sedimentary rocks may not be entirely discounted as a possible source, since remnants of late Precambrian sediments are known to occur in several locations along the flank of the gravity low, the gravity minima are believed to be largely controlled by masses of granite emplaced during a period of late Precambrian mountain building.

Another investigation of the gravity anomaly field in the province of Quebec is in progress at the University of Western Ontario. The regional gravity picture of the Gaspé region and Eastern Townships is being examined in relation to the surface lithology and to the tectonic history of the region.

(v) *Maritimes*—From January 1954 to December 1956 the Nova Scotia Research Foundation has occupied several thousand gravity stations in the Mississippian and Pennsylvanian sedimentary areas of Hants, Antigonish, Inverness and Colchester counties. Because of the large density contrast between these sediments and the basements and within the sedimentary section, valuable geological information regarding structure and the nature of faulting in these areas has been obtained.

(vi) *A Gravity Map of Canada*—In reports of the Dominion Observatory dealing with regional investigations, the gravity results are usually presented in tabular form and illustrated on Bouguer anomaly maps. As indicated in this and previous reports, areas for which regional studies have been completed and results published, now cover a considerable part of the country. It has, therefore, been possible to proceed with the compilation of a Bouguer anomaly map for Canada (22). While only the southern portion has been surveyed in sufficient detail to draw contours of equal gravity, the anomalies for all stations are illustrated. The map is on a scale of 100 miles to an inch with a contour interval of 10 milligals. A colour scheme similar to that used for topographical maps permits the easy identification of highs and lows and emphasizes large scale gravitational features indistinguishable on more detailed maps.

#### (b) *Isostatic Studies*

Until 1950 the only gravity observations isostatically reduced in Canada were those at pendulum stations (see Figure 2) and a few scattered gravimeter stations. Recently isostatic studies have been resumed by the Dominion Observatory and isostatic anomalies are now available for nearly 1,200 gravity stations. Of these, 203 lie in the mountainous regions of British Columbia while 850 are distributed over a wide area of the Canadian Shield in northern Manitoba and Ontario.

Formerly most isostatic reductions by the Dominion Observatory were carried out following the Pratt-Hayford method for a depth of compensation of 113.7 km. Recent work has been to extend these reductions to include the Airy-Heiskanen system assuming crustal thicknesses for zero elevation of 20, 30, 40, and 60 km. For wide areas of low relief throughout the central plains and the Canadian Shield south of latitude 60 degrees, isostatic correction maps for the numbered zones, 1 to 18, are being prepared. These are based upon reductions previously completed for pendulum stations and for other stations located at every two-degree interval of latitude and longitude. When completed these maps will permit a rapid reduction of the isostatic anomaly for most gravimeter stations in the area.

#### (c) *Geoidal Studies*

Gravity measurements are being used for the first time in Canada for application to problems of geodesy. In the fall of 1956 a program was initiated at the Dominion Observatory to carry out a three-dimensional Fourier analysis of gravity data for western Canada. The method to be followed is one developed by Prof. C. Tsuboi (23). As the

method is applicable to limited areas it provides only relative values for geoidal heights and deflections of the vertical. The region selected for this preliminary investigation is a rectangular area in western Canada bounded by longitudes 95 degrees and 111 degrees west and latitudes 49 degrees and 63 degrees north. High speed computing machines are to be used in the analysis.

## INSTRUMENTAL DEVELOPMENT

### (a) *Pendulum Apparatus*

Considerable progress has been made during the last three years in the design and improvement of gravity measuring instruments. The construction of a bi-pendulum apparatus for relative measurements has recently been completed (24) by the Dominion Observatory and the University of Western Ontario. Interchangeable pairs of bronze half-second pendulums are swung in anti-phase in a temperature controlled vacuum chamber. The temperature, pressure, and mean arc are maintained constant within tolerable limits for every observation, so observed periods require no corrections. The Dominion Observatory has now completed exhaustive laboratory tests with the apparatus, and field trials along the Ottawa-Washington calibration line are in progress.

### (b) *Vibration Gravimeter*

Research in the development of a vibration gravimeter, suitable for measuring gravity on unstable ground or in a submarine at sea, was first attempted at the University of Cambridge (25, 26). This work has been continued in Canada at the Dominion Observatory and some progress has already been made. The Cambridge model has been modified to include new features which appear desirable in the submarine apparatus.

### (c) *Calibration Device for North American Gravimeters*

Another important development at the Dominion Observatory is the construction of a calibration device for a long-range North American Gravimeter. It permits a check to be made on the instrument's calibration at any time or place during a survey. This has been achieved (27) by placing an extra mass (a sapphire ball) on the beam and measuring the resultant deflection. Tests indicate that the arrangement provides a calibration accurate to one part in 2,000 or better. It has demonstrated very clearly that a definite change in the calibration of some North American gravimeters takes place if they should be permitted to overheat.

### (d) *Airborne Gradiometer*

What may prove to be a major advance in the design and construction of gravity measuring devices was announced (28) by the mining industry at a recent Ottawa meeting. It was reported that an Airborne Gradiometer has been developed, which is capable of measuring the variations of the vertical gradient of gravity, while the instrument is being transported. This apparatus is small and compact and provides a continuous record of the gradient along the flight path of the aircraft. Tests over certain known geological features have been carried out.

The successful development of such an instrument is of great importance and interest, not only to the exploration industry but to all scientists engaged in structural studies of the crust. Details concerning the design and performance of the gradiometer, therefore, are awaited with keen interest.

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