CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
DOMINION OBSERVATORIES

PUBLICATIONS

OF THE

Dominion Observatory

VOLUME XXIV No. 3

GRAVITY MEASUREMENTS IN CANADA JANUARY 1, 1957 TO DECEMBER 31, 1959

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National Report for Canada
for the
International Association of Geodesy
Twelfth General Assembly
International Union of Geodesy and Geophysics
Helsinki, 1960

THE QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
OTTAWA, 1960

CONTENTS

Illustrations

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SUB-COMMITTEE ON GRAVITY

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INTRODUCTION

In Canada coordination of the geophysical sciences is achieved through the Associate Committee on Geodesy and Geophysics of the National Research Council. Within this national committee the interests of each discipline are taken care of by sub-committees. The composition of the sub-committee on gravity is presented on the facing page. The sub-committee collects information for an annual report on gravity that is included in the Canadian Geophysical Bulletin (Garland 1957, 1958, 1959, editor) published by the National Research Council.

Gravity activity for the periods 1951-53 and 1954-56 has been reported to previous General Assemblies (Innes 1954, 1957a). According to instructions received recently this will be the last national report to be submitted directly to the I.U.G.G.; in future, national reports on gravity will be sent to the International Gravimetric Commission in time for its triennial meeting one year prior to the General Assembly, and the Commission will compile the national reports into one volume for presentation to the I.U.G.G.

In recent years the number of gravity observations has been increasing almost exponentially. The work of the Dominion Observatory has been expanding steadily and universities, research foundations, and the mining and oil exploration industries have all been more active in making gravity measurements. Responsibility for connections between First-Order World Stations, for the National Primary Network and for small-scale regional mapping rests with the Dominion Observatory. Absolute determinations of the acceleration of gravity are carried out by the National Research Council. Many detailed surveys for crustal structure studies are carried out each year by public institutions and by the exploration industries.

ABSOLUTE MEASUREMENTS AND CONNECTIONS TO FIRST ORDER WORLD STATIONS

During the period under review a series of experiments to determine the acceleration of gravity by the free-fall method was continued by Dr. Preston-Thomas at the National Research Council. At the end of 1959 the experimental work on the second rule, an invar rod, had been completed. For this rule the optical system was redesigned, raising the effective aperture from F9 to F5, thereby ensuring that the rotation of the rule during the drop was limited to less than 0.5 minute of arc. Measurement of the photographic plates, compilation, and assessment of the data from the final series of experiments is being carried out as rapidly as possible so a report (Preston-Thomas and others) can be presented to the I.U.G.G. in Helsinki in July, 1960.

In 1957 pendulum observations were made with the Dominion Observatory bronze bi-pendulum apparatus to connect First-Order World Stations at Ottawa, Vancouver and Washington (Thompson 1959) and in 1959 observations were made with the same equipment at Ottawa, Teddington, Paris, Bad Harzburg and Rome. These observations are being compiled for a report to be presented to the Helsinki meeting. (Winter, Valliant and Hamilton, in preparation).

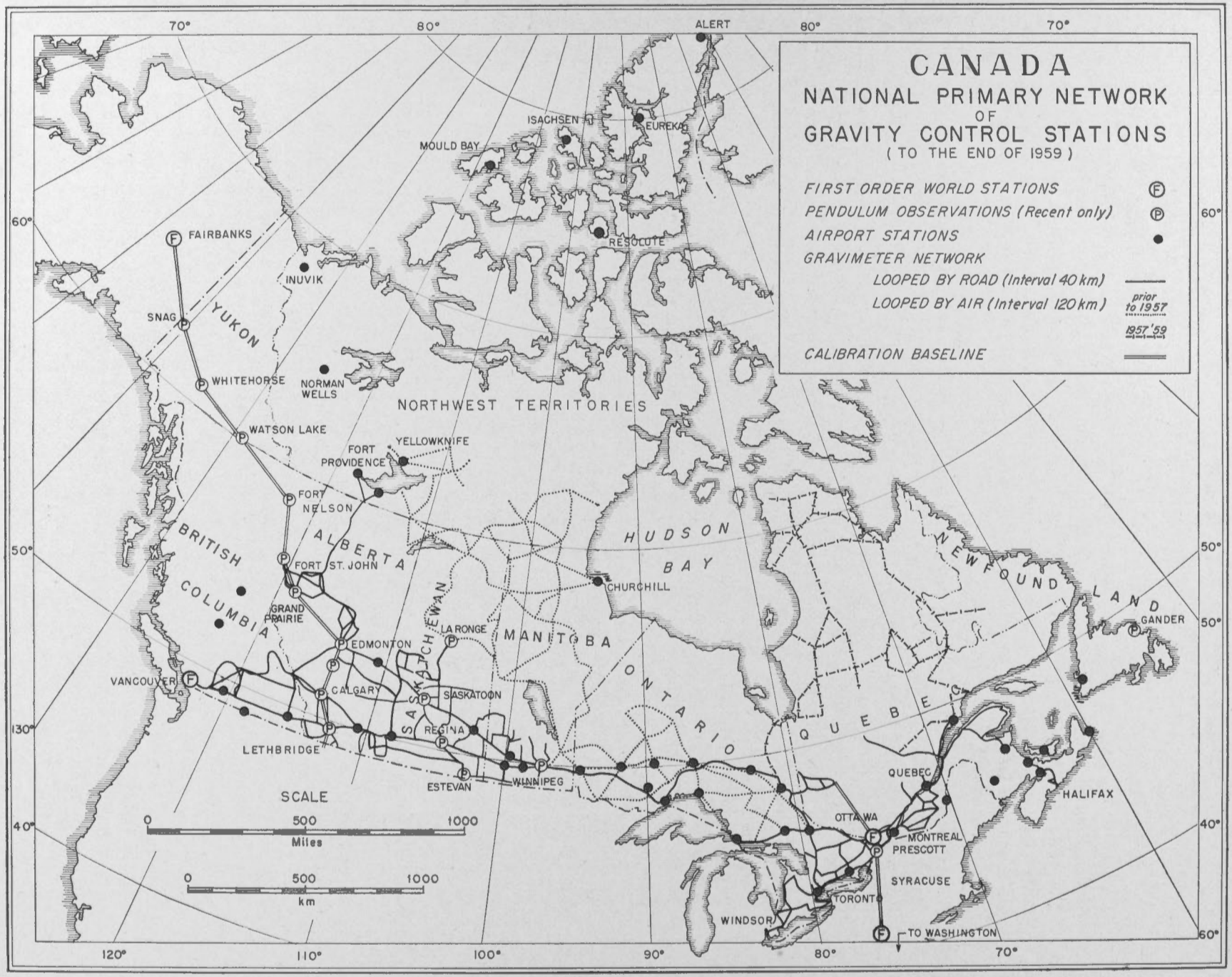

Figure 1. Gravimeter reference network and calibration base lines.

NATIONAL PRIMARY NETWORK

Establishment in Canada of a network of control stations consistent with First-Order World Stations is the responsibility of the Dominion Observatory. The Observatory's bronze bi-pendulum apparatus has been tested in the field and is being used to provide regional control for the gravimeter networks. Ultimately it is hoped that there will be, at intervals of a few hundred miles, a network of pendulum stations throughout the country; the immediate objective is a line of stations in the central section from Winnipeg to Isachsen, and in the eastern section from Ottawa, via central Quebec, to Alert.

Since most field surveys use aircraft and since gravimeter looping can best be carried out with air transportation the network of airport stations established in 1955 (Bancroft, 1960) is gradually being extended (Figure 1) to provide supplementary control for regional gravimeter surveys.

The North American calibration line (Garland 1953, 1955, *see* Figure 1) was orignally intended to provide a standard for all gravimeter calibrations. However, as it was remote from Ottawa and could not be used regularly, a second, more accessible base was established between Ottawa and Washington (Innes 1958). Since 1955 all gravimeters have been calibrated over this line before and after each field season. This has proved highly successful in maintaining internal consistency in regional networks.

The First-Order World Stations, pendulum stations, airport stations and gravimeter networks that are being used for control in Canada are shown on Figure 1.

Measurements made during the 1957-59 period are listed below.

Pendulum Measurements.

In addition to the measurements at First-Order World Stations referred to above, measurements were made at Prescott, Ont., Ithaca, N.Y., and Winnipeg, Man. in 1957 (Thompson 1959); and at Winnipeg, Man., Estevan, Regina, Saskatoon and La Ronge in Saskatchewan in 1958, (Winter and Valliant in press). The internal consistency of the pendulum periods indicates that the accuracy is approximately $\pm$ 0.4 milligal and comparisons with gravimeter measurements confirm that this accuracy is being achieved.

Airport Stations.

In 1957 gravimeter ties were made between Churchill and the Arctic weather stations: Resolute, Mould Bay, Isachsen, Eureka, and Alert by Bancroft (1958), using RCAF transportation. In 1959, using scheduled airline transportation, additional stations were established at Hay River, Yellowknife, Norman Wells and Inuvik (at the mouth of the Mackenzie River). In addition, a tie was made between Montreal, Que. and Gander, Nfld.

Gravimeter Networks.

All gravimeter control stations are established by the method of forward looping, ABAB. Networks of loops are closed and wherever overlapping of networks occurs an adjustment is carried out. Two major gravimeter networks were established during the years 1957-59:

Western Quebec.—In conjunction with regional mapping in western and northern Quebec a network of some 70 stations was established and adjusted (Figure 1).

Prairie Provinces.—A network of some 300 bases was established in the developed regions of the prairie provinces (Figure 1). This network has been adjusted and a report is in preparation.

REGIONAL MAPPING (1:500,000)

The Dominion Observatory has recently initiated a long-term program of field surveys to provide data to publish Bouguer anomaly maps at a scale of 1:500,000. Each map sheet corresponds in area to the maps of the national topographic series, usually covering an area two degrees of latitude by four degrees of longitude. The average grid interval between stations is ten miles or less; at mid-latitude this gives approximately 25 stations per degree square. This program has been followed in two major areas: the prairie provinces and northwestern Quebec.

Prairie Provinces.

As a contribution to the IGY the Canadian Association of Exploration Geophysicists arranged with the oil industry to release a large volume of data in the developed sections of the country at a density of one station per township (six-mile square). Since virtually none of this data was tied to the national network, the Observatory sent parties to the field to re-observe sufficient representative stations so the company data could be converted to a consistent datum. At the same time the Observatory crew surveyed numerous small areas for which oil company data was not available. By the end of 1959, for the area from 49°N to 52°N extending from 96°N to 116°W, some 5,000 stations, at least one per township, were available. From these observations principal facts were being computed and compilation of anomaly maps was under way.

Considerable data north of 52°N latitude has been provided to the Observatory by the oil companies and the program of tying it to the National Network and filling the gaps will be continued.

Northwestern Quebec. (North of 52°N; West of 72°W).

One survey party using two aircraft for transportation operated in this region during 1958 and 1959. A control network was established and 2,000 stations were observed. Data for five maps has been assembled, four in the southern part and one at the northern limit of the area (*see* Figure 2). The most interesting feature of the maps is a positive anomaly over the Cape Smith-Wakeham Bay belt on the most northerly map sheet. Preliminary analysis of the data indicates that the feature can be explained, partially at least, by surface rocks which have densities as high as 3.15 grams per cubic centimetre.

Data Processing

With the increased field activity during the past few years field data has been accumulating to the point where processing, sorting, and compilation have become a formidable problem. Investigations of improved methods of handling data have resulted in a

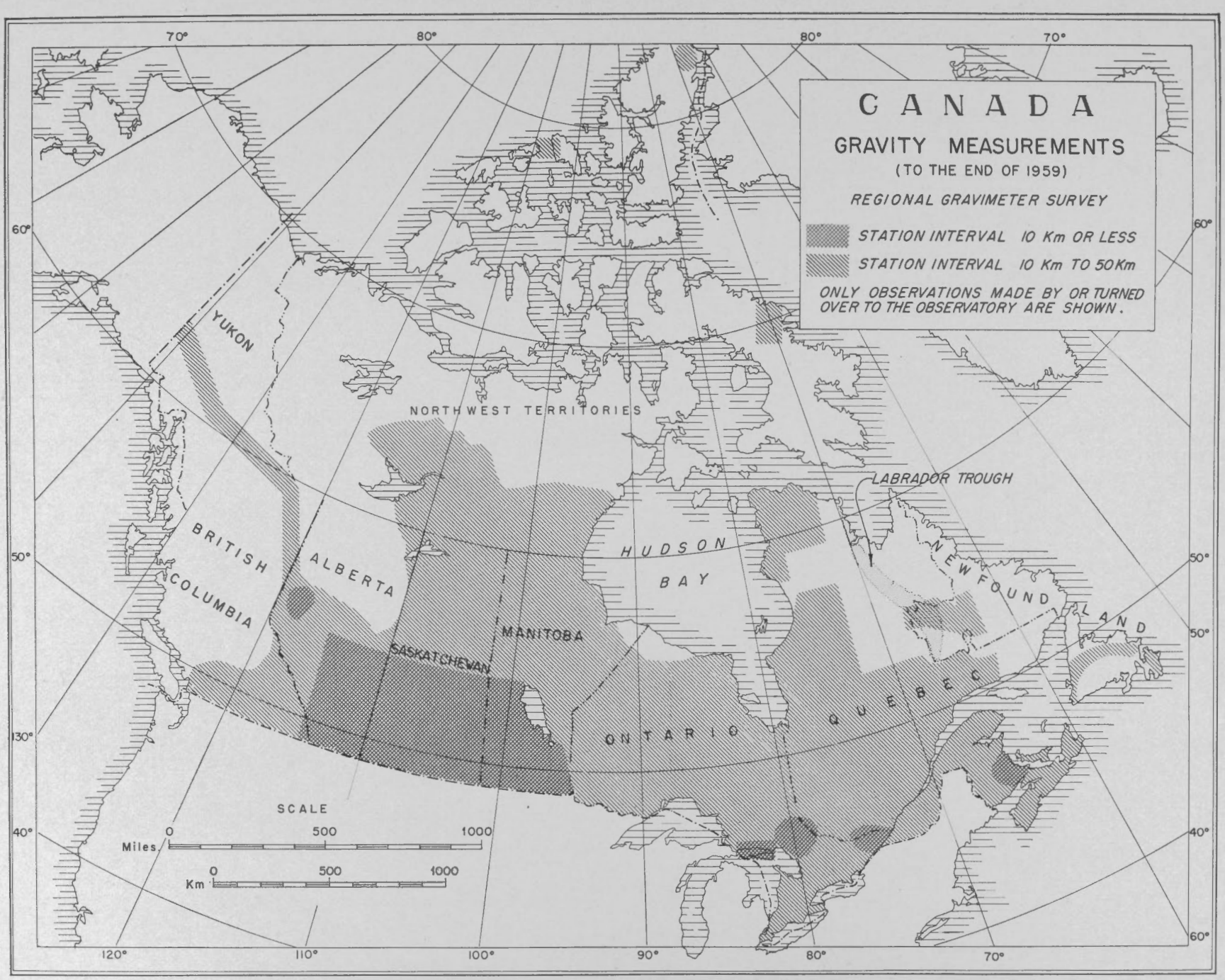

Figure 2. Gravity measurements in Canada to the end of 1959.

system whereby data from the field notes are transferred directly to IBM punch cards. This is the last manual operation on the data. Computation of principal facts is done by an electronic computer and the results, sorted as required, are printed in a form suitable for distribution. For example, data for map compilation are sorted into degree squares. Recent field data are now on this system and older data will be converted gradually.

OTHER MAPPING AND INVESTIGATIONS

Prior to embarking on the systematic regional mapping program (outlined above) the Dominion Observatory had been doing reconnaissance surveys and some detailed studies in areas of particular interest. In addition, several universities, one research foundation and many exploration companies have been doing detailed analyses for diverse purposes. In general, exploration companies cannot be persuaded to make their data public until they are certain that it is of no competitive value. Consequently, only investigations by universities and government agencies are available for the period under review. Several projects of interest are discussed briefly.

Gaspé Peninsula, Quebec.

The gravimeter survey of the Gaspé region initiated in 1956 was completed in 1957 by the Observatory. A Bouguer anomaly map of the area at 4 miles to the inch, based on some 600 stations, has been published with a report (Tanner and Uffen 1959). The outstanding feature of the map is the positive anomaly over the Shickshock Mountains. Calculations of the stress differences from isostatic anomalies (for 50 stations) show that the earth's crust could be sufficiently strong to support the mountain without any isostatic compensation. However, analysis of the Bouguer anomalies suggests that the main structure associated with the Shickshock Mountains may be a horst, in which case the mass excess could give rise to subsequent movement in the fault zone. The regional Bouguer anomaly trends can be explained by a rotational fault zone which has disturbed the hypothetical *intermediate layer*.

Manitoulin Island Area, Ontario.

In the area of the north shore of Lake Huron between 81° and 83° W longitude, south of 46° 30′ N latitude, 550 stations were established by the Observatory. The area lies along the southern boundary of the Canadian Shield and is underlain by rocks which vary in age from early Precambrian to Middle Palaeozoic. The sedimentary strata of the latter, which occupy the greater part of the area, dip to the south, away from the Precambrian rocks upon which they rest, to form the northwestern portion of the Michigan Basin. Investigation shows that the major control of the gravity field stems from changes in lithology within the Precambrian basement. The outstanding gravity feature is the negative anomaly area to the southeast believed to reflect low-density granite masses within the basement rocks.

Labrador Trough Area.

In 1959 one party from the Observatory established 250 stations in the iron-rich region of central Quebec and Labrador known to geologists as the Labrador Trough.

At some of the stations to the east of the Trough (*see* Figure 2) strongly negative anomalies were observed that may be an extension of the negative anomaly belt extending north-easterly from the Lake Mistassini area (Innes 1957c).

Monteregian Hills.

Gravity measurements carried out by Queen's University during the summer of 1959 consist of 915 stations established along a strip 40 miles wide and 85 miles long covering the area around the Monteregian Hills and paralleling the lower reaches of the Ottawa River. The main purpose of the survey was to determine whether the Hills are located on an extension of the Ottawa Valley graben. A preliminary analysis of the results indicate that this hypothesis is correct.

Eastern Townships, Quebec.

An analysis of the results of a gravity survey of the Eastern Townships of Quebec in which 800 stations were established by Queen's University, indicates that the large positive anomaly located along the Sutton Mountains is caused by a mass of ultramafic material possibly extending from the base of the crust to within 10 kms. of the surface. A combined gravity and magnetic survey along the St. Francis River seems to show that the upper portion of the ultramafic mass is serpentinized to some extent. The Sutton Mountain anticlinorium is apparently related to the deep-seated intrusive and may have been caused by its upward movement.

Nova Scotia.

In Cumberland, Colchester and Pictou counties some 2,000 stations were established by the Nova Scotia Research Foundation in 1959. Their observations will be adjusted to the National Primary Network and made available on map sheets at a scale of two inches to one mile. Because of the large contrast in densities in the sedimentary section, gravity observations have been most useful in determining geological structure.

Ellesmere Island.

Gravity surveys were carried out in 1957-58 on northern Ellesmere Island by members of an expedition known as *Operation Hazen* which was supported by the Defence Research Board. A control station at the expedition's main base on Lake Hazen was tied to the Dominion Observatory station at Churchill by gravimeter looping and a network of control stations was established between Lake Hazen and Clement Markham Inlet on the north coast. A large number of stations were observed over the whole of Gilman Glacier and on the ice cap as far west as Mount Oxford. The purpose of this survey was to establish a relationship between the thickness of the ice and the change in gravity and to investigate the usefulness of a gravity survey as a supplement to seismic observations. Gravity observations were also used to get an estimate of the thickness of the ice on the ice cap in areas where no seismic soundings had been made.

Athabasca Glacier Expedition, British Columbia.

As part of their glaciological program, the University of Alberta carried out a gravity survey in 1959, between the toe of the glacier and the ice falls. Bouguer anomalies and

terrain corrections were computed. The gravity observations are controlled by a few seismic depth profiles, and by one hole drilled through the ice (glacier thickness at the hole is 1,024 feet).

The Mining Industry.

More than 50,000 gravity observations were made during the 3-year period. Most of this work was carried out to delineate known ore bodies, notably iron-ore formations in the Quebec-Labrador area. For many companies, a gravity survey, prior to drilling, is standard procedure.

The Oil Exploration Industry.

In recent years gravity surveys have been used only for reconnaissance prior to seismic surveys in oil exploration. Several surveys of this type were made in the northern part of the Yukon Territory and in the delta area at the mouth of the Mackenzie River.

Fossil Meteorite Studies.

Considerable progress was made in furthering our knowledge of fossil craters which may have resulted from the impact and explosion of meteorites during the earth's early history. It is found that such features (Millman and others, 1960) produce negative gravity fields. This is due to low density rock filling the depressions and to fragmental material and disturbed bed rock conditions which resulted from uplift and fracturing of the crust at the time of their formation. Gravity measurements in March, 1959, on the ice at Deep Bay, a crater eight miles in diameter forming the southeastern part of Reindeer Lake in Saskatchewan (Innes, 1957b), indicate a gravity minimum of more than 30 milligals which strengthens the meteoric theory of origin for Deep Bay.

In conjunction with regional surveys in Northern Quebec, four other circular topographic features which may have a similar origin were investigated. In addition to depth soundings, detailed gravity measurements were carried out in the vicinity of Clearwater Lake, Lac Couture (about eight miles in diameter) and also over a very old circular feature about three miles in diameter near Lake Menihek. In addition some seventy observations were made around the margin of West Hawk Lake on the Trans Canada Highway near the Manitoba-Ontario boundary. No results of these investigations are yet available.

Earth-Tide Measurements.

During the IGY the Dominion Observatory maintained two recording gravimeters in operation, one continuously in Ottawa, and the other, for periods of three to four months, at Resolute, N.W.T., and Meanook, Alberta. The scaling of the records and the reduction of the data to gravity units has been completed, and the information forwarded to world data centres.

ISOSTATIC AND GEODETIC STUDIES

Isostatic and Free Air Anomalies.

During the period under review a statistical analysis of isostatic and free air anomalies was carried out for a large region of the Canadian Shield to examine trends which might be related to incomplete isostatic adjustments of the crust following deglaciation (Innes 1960). On the assumption that the greatest Pleistocene ice loads were centred

in Hudson Bay, mean anomaly values were determined for six zones, each 100 miles wide, between the Hudson Bay coast and the southern boundary of the Shield. Both the free air and isostatic anomalies show a marked decrease in mean values across the zones, toward Hudson Bay. If it can be assumed that this departure from isostatic equilibrium is entirely due to horizontally displaced subcrustal material, the gravity data suggest that the crust in the vicinity of Hudson Bay has yet to rise about 800 feet before isostatic balance is restored.

Geoidal Heights by Fourier Analysis.

A three-dimensional Fourier analysis of gravity data for a large area of the western plains and a portion of the Canadian Shield has been completed (Shimazu in press). Using Bouguer anomalies and elevations averaged for a rectangular array of some 400 points at intervals of 72 km., the analysis yields values for deflections of the vertical which do not exceed four seconds, corresponding undulations in geoidal heights varying from +5 metres in the south to +8 metres in the north-east near Hudson Bay. These results are, qualitatively, in agreement with values based on astro-geodetic data (Fischer 1957). They are also consistent with the marked negative trend of the isostatic and free air anomalies discussed in the preceding paragraph.

Orthometric Corrections.

At the Ontario and Quebec boundary in the Lake Temiskaming area the Observatory and the Geodetic Survey of Canada established 160 stations adjacent to bench marks of the precise level network of the Geodetic Survey of Canada. Orthometric corrections for a section of levelling in which there was an unusually large misclosure were recomputed using observed gravity instead of theoretical gravity. However, this failed to improve the closure and since independent checks on each section of the levelling verify the validity of the levelling itself the explanation for the misclosure must be due to differential crustal movement in the area. Since part of the level network was observed in 1921-22 and another part was done in 1958 it is perhaps significant that in 1935 one of the few earthquakes ever recorded in the Canadian Shield (Hodgson 1936) had its epicentre in the region of the investigation.

INSTRUMENTAL DEVELOPMENT

Pendulum Apparatus.

The Observatory's bronze bi-pendulum apparatus has been tested and used in the field for three seasons (Thompson, 1959; Winter and Valliant, in press; Winter, Valliant and Hamilton, in preparation).

When the case and pendulums were ready for testing in 1956 a recording and timing system was improvised so that the tests might be begun. Some components of this system have proved unreliable and much of it has become obsolete by modern standards. Early in 1959 a development program to redesign all the auxiliary equipment was initiated. An electronic device to give an instantaneous record of time and amplitude of swing for each pendulum is being designed to replace the photographic recorder and an improved frequency standard, for which stability within 5 parts in 10^{10} per day has been claimed, is being adapted for the apparatus.

Vibration Gravimeter.

Development of a gravimeter in which the change of frequency due to a change in the tension of a vibrating element is measured, has been under way for several years at the Observatory. In the period under review, the vibrating element and associated electro-mechanical components have been completely redesigned. Performance tests have been carried out and in the latter part of the period efforts have been directed toward improvements in the auxiliary equipment.

A recording camera unit has been built and a transistorized frequency standard has been adapted for use with the instrument. Completion of a new driving oscillator and amplifier for the vibrating element will enable an accurate evaluation of the gravimeter to be made.

Airborne Gradiometers.

Two organizations are developing instruments for measuring changes in the vertical gradient of gravity. Lundberg Explorations Limited report that an airborne gravity gradiometer suitable for reconnaissance surveys has been developed. Several test flights have been made over areas known to have large Bouguer anomalies. From the anomalies at the surface, vertical gradients at the height of the aircraft can be computed (Baranov, 1953) and from the comparison of the observed and computed gradients, it is expected that a quantitative appraisal of the instrument will soon be available.

The Research and Development Division of Hunting Associates Limited have completed the first stage in the development of an airborne gradiometer based on new instrumentation principles upon which patent action has been initiated. The equipment will weigh about 600 pounds not including gyro stabilizing gear. It is designed to respond to vertical gravity gradients of about 1.5×10^{-5} milligals per foot at a time constant of 10 seconds. Development work is proceeding with this instrument in order to provide an exploration tool for the oil and mining industries.

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