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GRAVITY MEASUREMENTS IN CANADA

January 1, 1963 to December 31, 1966

Compiled by
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GRAVITY MEASUREMENTS IN CANADA, JANUARY 1, 1963 TO DECEMBER 31, 1966

Introduction

At the request of the International Union of Geodesy and Geophysics (IUGG) this report has been prepared for the Fourteenth General Assembly on behalf of the Associate Committee of Geodesy and Geophysics (ACGG), the National Committee representing Canada in the international union. This report is based on those of the subcommittee for Gravity of the ACGG, published annually in the Canadian Geophysical Bulletin (G. D. Garland, Editor). The membership of this subcommittee includes representatives from various universities and government institutions and one member each for the petroleum and mining industries. The present membership is:

A. E. Beck	University of Western Ontario
B. Bidgood	Nova Scotia Research Foundation
K. B. S. Burke	University of Saskatchewan
M. Caputo	University of British Columbia
E. R. Deutsch	Memorial University of Newfoundland
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G. Konecny	University of New Brunswick
B. D. Loncarevic	Bedford Institute of Oceanography
N. R. Paterson	Huntec Limited
J. G. Tanner	Dominion Observatory, Chairman
H. D. B. Wilson	University of Manitoba

The largest contribution to this report comes from the Dominion Observatory which is the federal agency responsible for the development of instruments to make gravity measurements, for mapping the gravitational field of Canada, and for the interpretation of the measurements in studies related to crustal and geological structures and to geodetic investigations. Regional mapping by the Observatory during the years 1963-66 covered about one and a half million square miles of land and inland coastal water areas. Most of the observations in the areas surveyed were spaced at intervals of about 10 km. These observations have provided the basis for several research papers which have recently been or are almost completed. Instrumental development included the reconstruction of the pendulum apparatus, investigations of the performance of gravimeters, further development of the vibrating string gravimeter and the establishment of an earth tide laboratory. The Observatory also participated with the Bedford Institute of Oceanography in a comprehensive study of gravity measurements at sea using surface vessels. Finally efforts to improve the domestic network of control stations and to strengthen ties with the First Order World Gravity Network (FOWGN) continued.

The Bedford Institute of Oceanography is engaged in a major marine geophysicial program in the Atlantic Ocean. As part of this program, gravity observations are made using an Askania surface-ship gravimeter. This institute's contribution consists of several very long traverses and several detailed investigations in selected areas.

Important local investigations were carried out by the Nova Scotia and the Saskatchewan Research Foundations. In Nova Scotia the gravimetric work was used in studies of certain sedimentary areas. In Saskatchewan measurements were made over a large intrusion and over gravel deposits in old stream beds.

Nearly all the universities in Canada were involved to some extent in the application of gravity data to crustal or geological problems. Some studies such as those at the Universities of Manitoba and Alberta, were made in conjunction with seismic and other geophysical observations and other studies such as those at the Universities of Toronto and British Columbia and Memorial University involved gravity measurements alone. At the University of New Brunswick gravity observations have been used exclusively for geodetic studies.

The progress made by these various organizations with their investigations is reported. Generally the report is restricted to published papers and to those papers in press for which oral presentations have been given at scientific meetings. Maps and diagrams to locate the projects geographically are also included.

Instrumental Development

Pendulums

An extensive program of research and development, under the direction of H. D. Valliant, was begun in 1960 to improve the over-all accuracy of the Canadian Bronze

Pendulum Apparatus. The initial objective was to replace the photographic method for measuring pendulum periods with a completely electronic system. This phase of the project was completed by 1963 and it soon became apparent that other parts of the apparatus, especially the temperature control system, were inadequate. The pendulum apparatus was subjected to a complete overhaul. A new pendulum case, temperature control system and digital recorder were designed and constructed. A recent photograph of the pendulum apparatus is shown in Figure 1.

Extensive testing of this equipment has been underway since early 1966. The main objective was to establish the long-term stability that could be expected from the bronze pendulums. Some 200 observations were made at Ottawa between February and December 1966 with one set of three pendulums. The fictitious periods (i.e., the mean period of two pendulums swinging in antiphase) were found to be normally distributed about their mean with a standard deviation of 6×10^{-7} sec. Each gravity observation consists of 72 such measurements. A second series of tests, in which the gravity

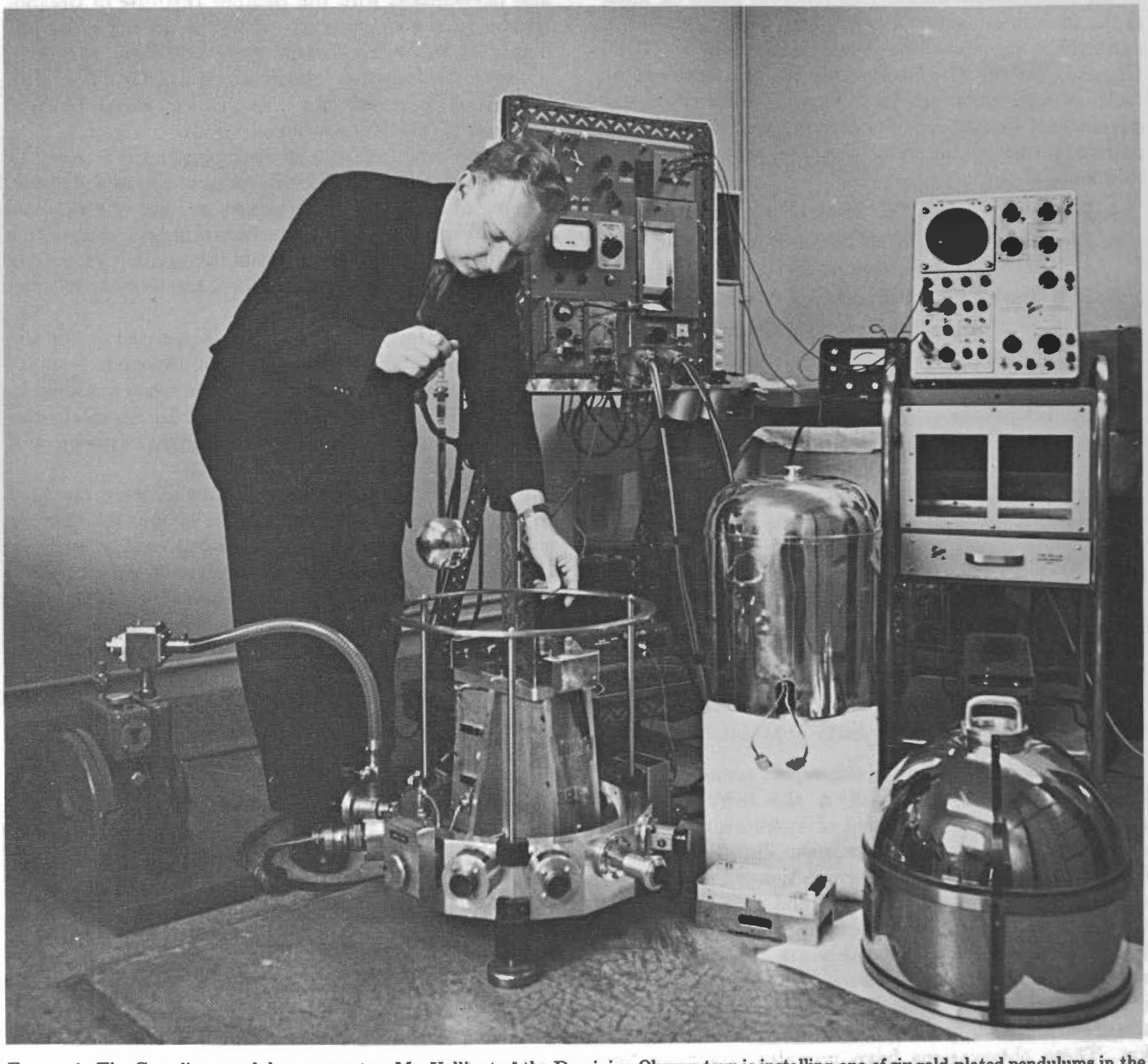

FIGURE 1. The Canadian pendulum apparatus. Mr. Valliant of the Dominion Observatory is installing one of six gold-plated pendulums in the pendulum case. The oven (centre) maintains the temperature at 40°C (±0.01°C) and completely surrounds the pendulums. The oven, in turn, is enclosed by a gold-plated bell jar (right foreground) which provides a vacuum-tight seal. The vacuum pump is in the left foreground and the electronics for temperature control and period measurements are located on the panel in the rear.

difference between Ottawa and Almonte (a town about 30 miles southwest of Ottawa) is measured several times with the pendulums as well as gravimeters, has recently been completed. The results show systematic differences, amounting to 0.2 mgal or more, between pendulum and gravimeter observations. Since design specifications, verified subsequently by comprehensive testing, have practically eliminated factors such as temperature and pressure as significant sources of systematic errors, it is believed that the knife edges and the pendulum flats are the cause of the errors. Experiments to test this hypothesis are currently underway.

Gravity at Sea

Development of a vibrating-string gravimeter for use at sea was suspended temporarily in 1963 to investigate the problem of correcting for its nonlinear response. This investigation led to a study of nonlinear effects in sea-gravity measuring systems in general (Bower and Watt, 1963) and later, in co-operation with the National Research Council, to the development of an inertially-stabilized vertical reference for testing these systems at sea. An extensive sea test of both the LaCoste and Romberg and the Askania-Graf type gravimeter systems was completed in 1963 with the co-operation of the Bedford Institute of Oceanography. Analysis of this and subsequent shorter tests, which were carried out along the Halifax Sea Gravimeter Testing Range (Goodacre, 1964a) identified several sources of error which could either be remedied by the gravimeter manufacturer or overcome by improved survey techniques and by auxiliary measurements (Bower, 1966). Preliminary results were presented by Bower (1964) and Loncarevic (1964) and a full account by Bower and Loncarevic (1966). After these tests D. R. Bower of the Observatory developed a shipborne analogue digital computer to determine the magnitude of the cross-coupling effect. This computer was installed and tested aboard the CSS *Hudson* by Mr. Bower and it has been successfully used during subsequent surveys.

Because of the demonstrated success of the linear gravimeters tested it was decided that further development of the vibrating-string gravimeter as a sea gravimeter was not warranted. Development of this gravimeter is continuing, intermittently as time permits, for use as a bore-hole gravimeter and as a tiltmeter for the measurement of deflections of the vertical with respect to the earth's surface.

Earth Tides and Crustal Tilt

As a contribution to upper mantle studies the Observatory has initiated a program to record earth tides and crustal tilt for a study of the physical properties of the earth's deep interior. During 1966 a site was established in an abandoned mine near Ottawa and equipped with a pair of Verbaabdert-Melchior horizontal pendulums and a LaCoste and Romberg earth tide gravimeter together with automatic equipment for control, digitizing and recording. When this site is operational, it is planned to extend the earth tide program to include a study of the properties of the earth's interior in relation to the geological environments in Canada.

The Nova Scotia Research Foundation has also initiated a program to measure crustal tilt. Two tiltmeters have recently been purchased and the daily recording of tilt is expected to begin in 1967.

Connections to First Order World Stations

Since the Dominion Observatory's pendulum apparatus has been undergoing reconstruction during the period under review, all connections made to First Order World Stations (FOWS) have been made using LaCoste and Romberg land gravimeters. These instruments are practically drift-free and are threfore nearly ideal for international gravity connections where the time interval between successive readings is often a matter of hours and repeated readings at the stations may only be possible in a period of a day or more. Like all instruments used to measure gravity they occasionally give a result which is internally consistent but, for some hitherto unknown reason, disagree with other connections over the same gravity interval. Recent laboratory tests (Hamilton and Brulé, 1966) appear to have provided an explanation of this erratic behaviour by the LaCoste and Romberg gravimeters. All the Observatory's meters were subjected to forced vibrations in the range 35–70 c/s and accelerations in the range ± 2 g and under these conditions all were found to drift erratically. Maximum changes in reading of about 5 mgal in a period of less than an hour were recorded. Vibrations and accelerations within the ranges given above are commonly experienced in commercial aircraft and land vehicles and the authors concluded that such disturbances are the main cause of erratic behaviour of these instruments. Further tests showed that the performance of the gravimeters could be vastly improved by installing mechanical isolators in the carrying case. This improved equipment was used for most international connections made in 1966. The connections made before 1966 are being carefully reviewed and will be repeated where evidence of erratic behaviour exists.

The international connections are given by years below. Transportation was provided mainly by commercial flights. One series of connections was made in a co-operative program with United States scientists using a United States Air Force aircraft and another project was carried out in conjunction with the Dominion Observatory's airborne magnetic survey of the North Atlantic and Scandinavia.

1. International connections in 1963 were:

(i) All stations of the European calibration line (ECL) between Bodo, Norway and Catania, Sicily.

(ii) The western North American calibration line (WNACL) between Fairbanks, Alaska and Mexico City, Mexico.

(iii) Observations between Ottawa in Canada, Quito in Ecuador and Buenos Aires in Argentina and in a co-operative program with Professor Baglietto of the Argentinian Institute of Geodesy, preliminary work on a calibration line covering the latitude range of Argentina.

2. International connections in 1965 were:

(i) The WNACL was observed between Point Barrow, Alaska and Denver, Colorado and this calibration line was connected to the northern end of the ECL by observations in the northern Arctic.

(ii) The ECL between Hammerfest, Norway and Catania, Sicily.

(iii) The Ottawa-Washington calibration line was re-observed and all stations monumented.

(iv) In co-operation with scientists of the United States the northern half of a proposed eastern North American calibration line was observed between Montreal and Alert in Canada.

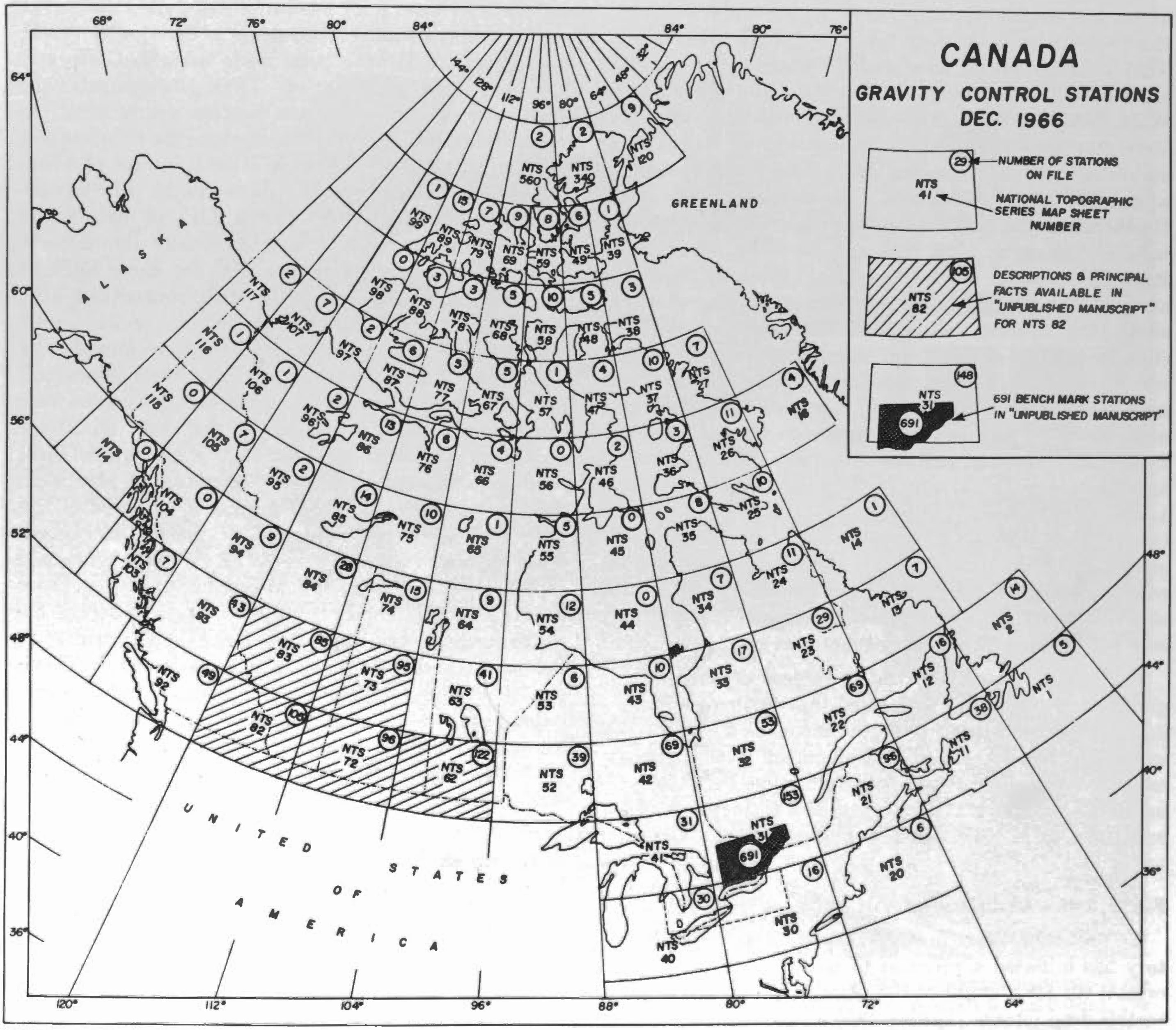

FIGURE 2. The distribution of control stations, by map sheet, established by the Dominion Observatory within Canada.

3. International connections in 1966 were:

(i) All stations along the WNACL and the Ottawa-Washington calibration line were reobserved.

(ii) Connections were made between the WNACL and the ECL via Greenland.

(iii) Observations were made at stations along the western Pacific (WPCL) and Australian north-south calibration lines.

National Primary Network

Considerable progress has been made since 1962 in extending the gravimeter network to all parts of Canada (Figure 2). The measurements at control stations have all been made with LaCoste and Romberg gravimeters as part of the Observatory's program of regional mapping and as part of a program devoted specifically to connections between primary stations in Canada and elsewhere. The data have not been adjusted to form a single homogeneous network pending additional pendulum observations.

Station descriptions are published in preliminary manuscript form with copies available on request only. The primary stations and excentres are assembled in one file and the regional control stations in another. The excentre file is currently undergoing final revision, under the direction of A. C. Hamilton, preparatory to publication. The regional control stations are filed by map sheet (4° latitude by 8° longitude) according to the National Topographic System for Canada. This file contains all stations established prior to 1966; stations observed in 1966 will be incorporated into the file by mid-1967.

Gravity Observations by the Dominion Observatory

This institution carried out a comprehensive field program during each of the years under review. The major part of the field operations was devoted to regional mapping (gravity observations taken at 10-km intervals). The main contribution to the regional work came from large helicopter-equipped surveys. Underwater surveys on inland and coastal waters accounted for about 10 per cent of the regional observations. Figure 3 shows the progress with regional mapping in Canada to the end of 1966, and Table 1 gives a summary of the geographic distribution of the observations during the period under review.

Although the Canadian Shield was the subject of many of the investigations, gravity work has been carried out in all main geological structural units in Canada. The Shield still proves to be a source of many interesting and unusual anomalies, both regional and local. Gravity mapping within the Canadian portion of the Appalachian System has been completed, except for a small region in the northern part of the Gulf of St. Lawrence. In 1966 a preliminary survey was made in the northern part of the Cordillera in western Canada to examine surveying problems prior to a large regional mapping program in the region.

Table 1

Regional Mapping by the Dominion Observatory

Region	Area (sq. mi.)	No. of Observations
Quebec and Newfoundland	225,000	4,700
Maritimes	35,000	600
Hudson Bay	200,000	1,300
Ontario	300,000	6,500
Prairie Provinces	200,000	5,000
Northwest and Yukon Territories	250,000	5,000
British Columbia	75,000	1,900
Polar Shelf	200,000	2,300

The Observatory has expanded its program to provide detailed information concerning local geological structures. The increase has resulted because the scope of the large regional surveys has been extended to include at least one investigation of a local nature. This practice has permitted observations of the gravity field over geological features to be made in much greater detail than would be possible with the smaller survey group normally mounted for detailed surveys. As an example, in 1965 the Observatory, in a co-operative program with the Saskatchewan Department of Mines, established a network of 700 closely spaced stations in the vicinity of a large norite body near Stony Rapids to obtain information concerning the configuration of this intrusion, the southern extension of which is overlain by Proterozoic sandstones. Other detailed surveys carried out during the course of larger regional studies include the surveys of the Kapuskasing feature in northern Ontario and of the Churchill-Superior boundary in northern Manitoba.

Detailed investigations carried out independently of regional surveys include the crater investigations and studies of intrusive masses in Ontario and Quebec. Crater research is a program of long standing at the Observatory. During the last four years the field work has been confined to completing the observations over those previously under investigation. With one or two exceptions, the gravity work is now completed, the results of which are reported in a subsequent section. Associated with the Kapuskasing feature are a number of alkaline intrusions which, elsewhere in the world, are often associated with rifts. In 1965 gravity observations were made over two of these. Other intrusions investigated include the anorthositic and related basic and ultrabasic rocks occurring in the Grenville geological province in the southern part of Quebec.

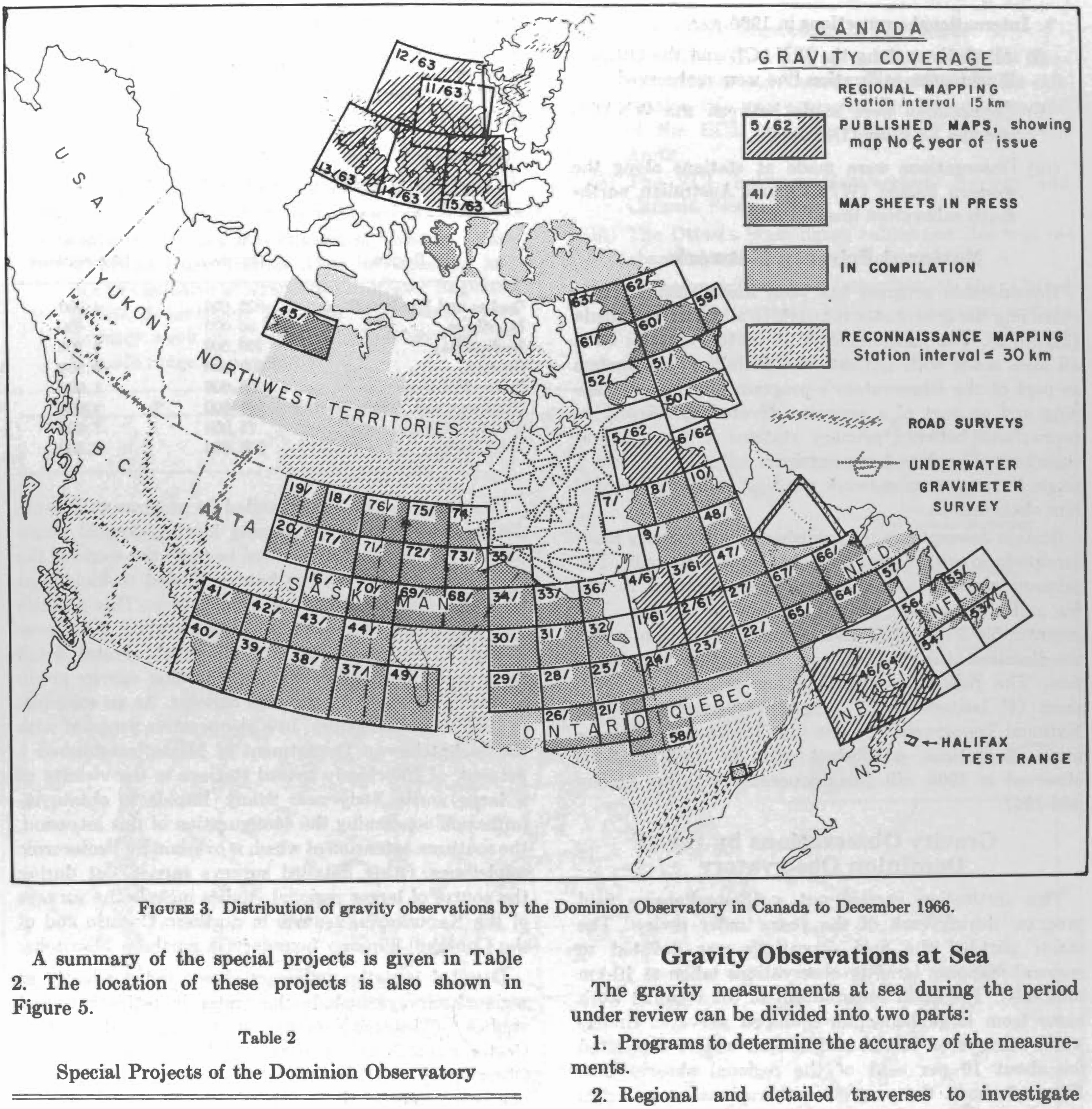

Figure 3. Distribution of gravity observations by the Dominion Observatory in Canada to December 1966.

A summary of the special projects is given in Table 2. The location of these projects is also shown in Figure 5.

Table 2

Special Projects of the Dominion Observatory

Subject	No. of Stations
Craters	850
Alexandria, Ont.	700
Stony Rapids norite intrusion	700
Kapuskasing feature (including alkaline intrusions) in northern Ontario	500
Anorthositic and related gabbroic intrusions in Quebec	200
Churchill-Superior boundary in northern Manitoba	500
Bench mark surveys	1,550

Gravity Observations at Sea

The gravity measurements at sea during the period under review can be divided into two parts:

1. Programs to determine the accuracy of the measurements.

2. Regional and detailed traverses to investigate regional and local structures.

All of the work was carried out either off the east coast of Canada or in the Atlantic Ocean basin.

The main sources of error in the measurements are the relatively short period movements of the surface vessel which produce accelerations recorded by the gravimeter in addition to real variations in the gravity field and by navigation which produces errors in the reduction of the data. The testing program has been devised to test these sources of error independently. The first

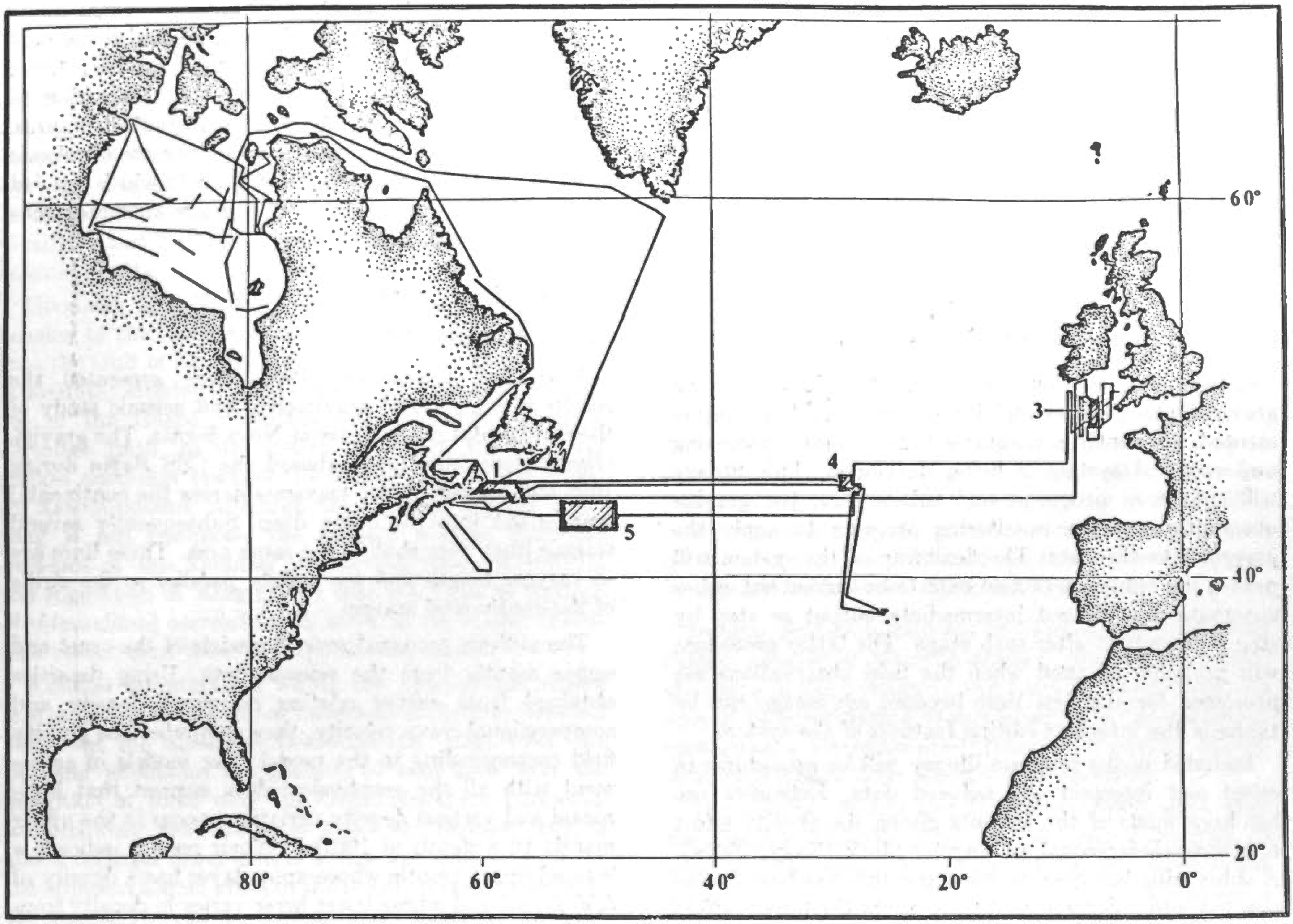

FIGURE 4. Distribution of gravity measurements at sea by the Bedford Institute of Oceanography.

phase was the establishment of a testing range (Goodacre, 1964a) about 60 miles off the east coast of Nova Scotia (Figure 4). This area was chosen for a variety of reasons, among which was the existence of a Decca chain which ensured that navigational errors were as small as possible. The area of the range is about 1000 square miles. Underwater measurements were made at 4-mile intervals throughout the area and, in addition, stations at one-mile intervals were observed along two Decca tracks. Subsequently the LaCoste and Romberg and the Askania surface ship gravimeters were extensively tested over the range in a joint Dominion Observatory-Bedford Institute program. The tests indicated that the Askania system was better suited for surface ship work than the existing LaCoste and Romberg system. They also demonstrated that both gravimeters could, with proper care in the measurements, provide sufficiently accurate results for most geophysical studies of the ocean basins. Finally the testing program led to suggestions for improvements in the instrumentation. The latter are briefly described in the section on instrumentation.

Navigational errors still provide the biggest uncertainty in the reduced results. The Bedford Institute is currently investigating various methods to improve the accuracy of navigation. Recently the Institute has attempted to use very low frequency (VLF-Omega) transmissions. This system is not yet operational but preliminary results indicate an accuracy of 1.2 miles under most conditions. Developments in satellite navigation are being closely followed and it is hoped that a system will be installed on the CSS *Hudson* as soon as the equipment is available.

The locations of traverses and areas of detailed surveys are shown in Figure 4. The areas of special surveys are as follows:

1. Orpheus anomaly.
2. Bay of Fundy survey.

3. Western approaches.
4. Mid-Atlantic Ridge.
5. Grand Banks.

Much of this work is part of a study of the Eastern Seaboard continental margin. This program was initiated in 1963 and is intended to provide systematic gravity coverage of the continental margin from the Gulf of Maine to Hudson Strait. The line separation within this area is approximately 50 km.

Data Processing at the Dominion Observatory

During the last four years a system for processing gravity data (Tanner and Buck, 1964) has been implemented. Currently a magnetic tape storage, processing and retrieval system is being developed. This library will consist of programs and subroutines, the gravity observations and a monitoring program to apply the programs to the data. The flexibility of the system will permit the reduction of field data to be carried out either automatically without intermediate output or step by step with output after each stage. The latter procedure will probably be used when the field observations are processed for the first time because advantage can be taken of the intensive editing features of the system.

Included in the program library will be procedures to select and interpret the reduced data. Extensive use has been made of the formula giving the gravity effect of a three-dimensional rectangular block (Nagy, 1966a). A subroutine has been written and this has been incorporated into programs used to compute the terrain effect (Nagy, 1966b) and in three-dimensional interpretation. Other programs that are or shortly will be included in the library are:

1. Two-dimensional gravity interpretation using the method sin x/x.

2. Self-adjusting methods of interpretation (Stacey, 1965; Tanner, 1967).

The preparation of maps has been facilitated by the acquisition of an electronic data plotter in 1963. This instrument is equipped with a symbol printer thus reducing the hand work on any map to contouring. Recently, however, the requirement for map contouring and plotted output for interpretation has increased considerably. Since the present plotter is not suitable for this, the Observatory hopes to purchase a more versatile plotter in 1967.

Application to Crustal and Geological Structure

In the past it has been the practice to include all crustal and geological interpretations in one section. In this report the interpretation of gravity data is divided into regional and local interpretations. Regional interpretations refer to those investigations related to regional crustal structure, but exclude isostatic studies. Local interpretations are those involving the application of the gravity data to the study of geological structures. The reason for this subdivision is the increase of seismic data available for many parts of Canada which has led to several papers devoted mainly to regional comparisons of the two sets of data.

Regional Interpretation

Eastern Continental Margin

Keen and Loncarevic (1966) have presented the results of a combined gravimetric and seismic study of the continental margin east of Nova Scotia. The gravity observations were made aboard the CSS *Baffin* during 1963 and consist of two traverses across the continental margin out into the ocean deep. Subsequently several seismic lines were shot in the same area. These lines are of varying length and are mainly parallel to the strike of the continental margin.

The authors prepared several models of the crust and upper mantle from the seismic data. Using densities obtained from curves relating measured density and compressional wave velocity, they computed the gravity field corresponding to the model. The models in agreement with all the geophysical data suggest that horizontal and vertical density variations occur in the upper mantle to a depth of 100 km. Their results indicate a layered upper mantle whose upper layer has a density of 3.30 g/cm^3 and whose lower layer varies in density from 3.42 g/cm^3 under the continental shelf to 3.32 g/cm^3 under the ocean basin.

The Appalachian System

Within the Appalachian region gravity investigations have been carried out by Goodacre and Nyland (1966), Goodacre (1964b) and Weaver (1966). The first two papers present the results of regional underwater surveys in the southern half of the Gulf of St. Lawrence. As has been found in other gravity interpretations in the Appalachians (Fitzpatrick, 1953; Tanner and Uffen, 1960) the regional Bouguer anomaly field does not correlate with the known thickness of sedimentary rocks which, according to density measurements from rock sampling and density determinations using seismic velocities, are 0.1 to 0.2 g/cm^3 less dense than the underlying crystalline basement rocks and thus should depress the gravitational field. Since the Bouguer anomalies are relatively positive in this area, Goodacre and Nyland were forced to conclude that either the middle and lower portions of the crust are more dense than usual or the crust is abnormally thin in this region. They also suggest that both conditions may obtain simultaneously. In a review paper Innes and Argun Weston (1966) point out that recent seismic work (Ewing, *et al.*, 1966; Keen and Loncarevic, 1966) indicates that an intermediate layer exists in this region but not under the adjacent shield areas, that the crust is thicker than normal and that seismic velocities in the upper mantle are higher than average, suggesting that the density in the upper mantle is higher than normal. The first suggestion made by Goodacre and Nyland is generally in agreement with the seismic results.

Goodacre and Nyland (1966) have mapped the extension of the "Gaspé High" (Tanner and Uffen, 1960) into the Gulf of St. Lawrence. In plan view the anomaly is arcuate; striking initially southeast from the eastern tip of the Gaspé Peninsula and gradually changing direction until, at its eastern extension, the anomaly strikes northeast towards the western side of the island of Newfoundland. Although the regional gravity mapping is not complete, the authors suggest that the presence of this anomaly in the Gulf tends to confirm the suggestion of King (1951) that the rocks in western Newfoundland correlate with those of the Gaspé Peninsula rather than those of Cape Breton Island.

Another investigation within the Appalachian region is Weaver's (1966) study of variations of the gravitational field over the island of Newfoundland. Regionally the Bouguer anomalies are positive or near zero with the exception of those over the Great Northern Peninsula in northwest Newfoundland where the regional level is about 30 mgal lower and is about the same as that for the adjacent Shield areas in the north. Weaver interprets the transition zone to represent the boundary between the Appalachian system and the Canadian Shield. The seismic results (Ewing, *et al.*, 1966) would seem to support this hypothesis. To the south of the proposed boundary the seismic work indicates that a thick crust with an intermediate layer is present whereas to the north the crust is thinner and the intermediate layer is absent. A comparison of the gravimetric and seismic data led Weaver to conclude that the two sets of data are compatible provided the density of the upper mantle north of the transition zone is less than that to the south. Depending upon the model assumed, lateral variations of density may be required at depths to 50 km.

The Canadian Shield

Quebec. The interpretation of a very large number of observations over the Precambrian Shield in the Province of Quebec is only partially completed. Tanner and McConnell (1964) have presented their interpretation of observations made over the northern Ungava Peninsula. The main feature of the Bouguer anomaly field is a positive gravity anomaly over a belt of volcanic and sedimentary rocks containing numerous small basic and ultrabasic intrusions. This gravity high is flanked on either side by negative anomalies. The analysis of the data suggests that the sedimentary-volcanic belt may have a maximum thickness of 7 km. The authors suggest that flanking negative anomalies are part of a larger regional negative anomaly and that this could be caused by faulting or warping at the base of the crust. Although they favour the structure at the base of the crust, Tanner and McConnell do not exclude the possibility of granitic rocks being the cause of this negative anomaly.

Elsewhere in Quebec Prof. F. Grant of the University of Toronto has reported on preliminary interpretations of gravity traverses across a negative anomaly coinciding spatially with the boundary between the Grenville and Superior geological provinces. The anomaly is attributed to a very thick sequence of sediments whose density is 0.1 g/cm^3 less than the surrounding rocks. This contrasts with a previous interpretation by Innes (1957) who suggested a buried granitic intrusion as the cause of the anomaly. Further investigations into the source of this interesting anomaly are continuing.

Ontario. Recently scientists of Canada and the United States conducted interdisciplinary studies of crustal structure in the vicinity of the Lake Superior basin. As part of its contribution to this program the Observatory conducted a reconnaissance underwater gravity survey in Lake Superior from the MV *Port Dauphine.*

The results (Weber and Goodacre, 1966) show that the Bouguer anomaly field over the lake is roughly 30 mgal greater than that observed in the surrounding area. Seismic results (Berry and West, 1966) along a roughly east-west line through the centre of the lake indicate that the basin is underlain by a sedimentary layer up to 10 km thick and that the crust thickens by about 25 km from west to east. On the assumption that the density of the upper mantle is greater than that of the overlying crust such a mass distribution would produce relatively negative Bouguer anomalies over Lake Superior. To reconcile this paradox the authors suggest that the sedimentary cover is underlain by rocks of higher than average density and postulate the presence of a basaltic layer which is much thicker under the basin than elsewhere.

Locally in the Lake Superior basin, positive anomalies appear to correlate with the occurrence of basic volcanic rocks and negative anomalies correlate with sedimentary rocks. Of particular interest is a linear positive anomaly, striking northeast, in the southwestern part of Lake Superior. Weber and Goodacre suggest that this is the continuation of the "Mid-Continental High" (Thiel, 1956) into the basin.

Manitoba. Hall and Brisbin (1965) compared their seismic results with the gravity data along a north-south profile in western central Manitoba. The profile crosses the presumed extension of the contact between the Superior and Churchill geological provinces. Regionally the Bouguer anomalies along the profile are relatively negative over the Churchill province to the north and rise gradually southward. Just north of the contact between the provinces there is a local positive anomaly and over the contact there is a negative anomaly.

From their analysis of the seismic data Hall and Brisbin distinguish the Conrad and Mohorovičić discontinuities. They find that the depth to the Moho decreases gradually from north to south. They place it at a depth of 35 km in the north and at a depth slightly in excess of 30 km at the southern end of the profile. The Conrad exhibits a similar trend, being at a depth of 15 km to the north and about 10 to the south. The theoretical gravity profile computed from this mass distribution is found to lie below the observed gravity profile in the Churchill province and above it in the Superior province to the south. Hall and Brisbin suggest that this discrepancy may be explained by the more frequent occurrence, in the vicinity of the profile, of basic volcanics north and relatively low density gneisses south of the contact.

Kornik and MacLaren (1966) have made a brief qualitative comparison of gravity and aeromagnetic with surface geology in the vicinity of the Churchill-Superior geological boundary. They find that the magnetic data correlate with near-surface geology but the gravity data do not. The apparent lack of correlation of the Bouguer anomalies with geological and aeromagnetic patterns leads them to suggest that the gravity anomalies are produced by density contrasts at depth.

Western Canada

Kanasewich (1966) presents a model of the crust and upper mantle across the southern part of western Canada. The model is based on the results of several seismic experiments and the gravity data published by Garland and Tanner (1957). This interpretation is prefaced by a review of all published results of seismic refraction experiments in North America. This review is presented in the form of two maps: one showing the compressional wave velocities (P_n) under the Mohorovičić discontinuity and the other, measured crustal thicknesses. These maps show P_n to be significantly lower under the Cordillera, suggesting an abnormally low density for the upper mantle in that region, and the crust to be thicker under the plains region and other low-lying areas than under the Cordillera, contrary to that expected according to the Airy theory of isostatic compensation. Since the geophysical data show that isostatic equilibrium approximately prevails throughout the region, Kanasewich concludes that while the Airy hypothesis is useful in explaining structural differences between oceans and continental margins, it fails in continental regions and that a modified form of the Pratt hypothesis, requiring density variations in the upper mantle, must be considered. These density variations are assumed to be caused by variations in the depth to and the thickness of Gutenberg's low-velocity channel.

The crustal model for western Canada is based on four sections: one under the Pacific Ocean, two under the Cordillera and one under the plains region in the east. Seismic experiments have been conducted in the area of each section. The densities assumed are based on standard P wave-density curves. The seismic and gravity data are compatible if the Gutenberg low-velocity channel is at a higher level under the Cordillera than elsewhere and if it gradually thickens westward from the plains area.

Queen Elizabeth Islands

Weber (1963), Sobczak (1963), and Sobczak, *et al.*, (1963) have interpreted gravity observations, made in conjunction with the Polar Continental Shelf Project, in the Canadian Arctic. Although the measurements cover a large part of the Queen Elizabeth Islands, the interpretation is confined to the northern islands of the group and to the continental shelf of the Arctic Ocean.

In the vicinity of the Sverdrup Islands the anomaly field is highly variable (Sobczak, 1963). Sobczak shows that, in general, areas of relatively negative anomaly can be correlated with thick sedimentary sequences and that areas of relatively positive anomaly correlate with dense basic igneous rocks.

A comprehensive study of the Bouguer anomalies over the Sverdrup basin, a major synclinorium some 800 km in length, indicates that the sedimentary sequence in the vicinity of Ellef Ringnes Island may have a maximum thickness of about 14 km. The uncertainty regarding the maximum thickness results mainly from the lack of adequate knowledge regarding the density distribution within the sedimentary column. Sobczak's models are in general agreement with the results of magnetic and seismic interpretations and agree well with estimates of thickness made by geologists from field studies.

Immediately north of the Sverdrup Islands Weber (1963) has reported on a very large positive anomaly which runs parallel to the continental shelf. The total change in anomaly across the strike is in excess of 100 mgal. Weber presents two alternative interpretations of the anomaly. The first assumes the anomaly is caused by the transition from a continental crust to an oceanic crust and requires that the crust thin from 30 km to less than 20 km over a distance of about 150 km. The second interpretation assumes, as Sobczak found over the islands to the south, that the positive anomaly is caused by basic igneous rocks. A basin-shaped intrusion with a maximum thickness of 10 km is suggested as a possible source. Since the magnetic field over the anomaly is quite flat, Weber concludes by suggesting that the first interpretation is more likely.

Geological Interpretation

Newfoundland

In addition to the regional interpretation described earlier, Weaver (1966) also carried out a comprehensive correlation of local Bouguer anomalies and surface geology. In general he found that the sediments have very little effect on the gravitational field and that granites are the main cause of negative anomalies. Most of the local, positive anomalies correlate either with dioritic intrusions or with gabbroic and ultrabasic intrusions.

Perhaps the most interesting aspect of the interpretation of local anomalies is their application as a test of conflicting geological theories regarding the origin of the Humber Arm group of sediments in southwestern Newfoundland. One hypothesis holds that these sediments were formed in situ and the other, known as the klippen theory, would have the sediments formed to the east and moved to their present location by first being squeezed up and out of their original basin and then moved by gravity sliding into their present location. These sediments are intruded by several basic and ultrabasic intrusions. If these intrusions are part of the klippen, as

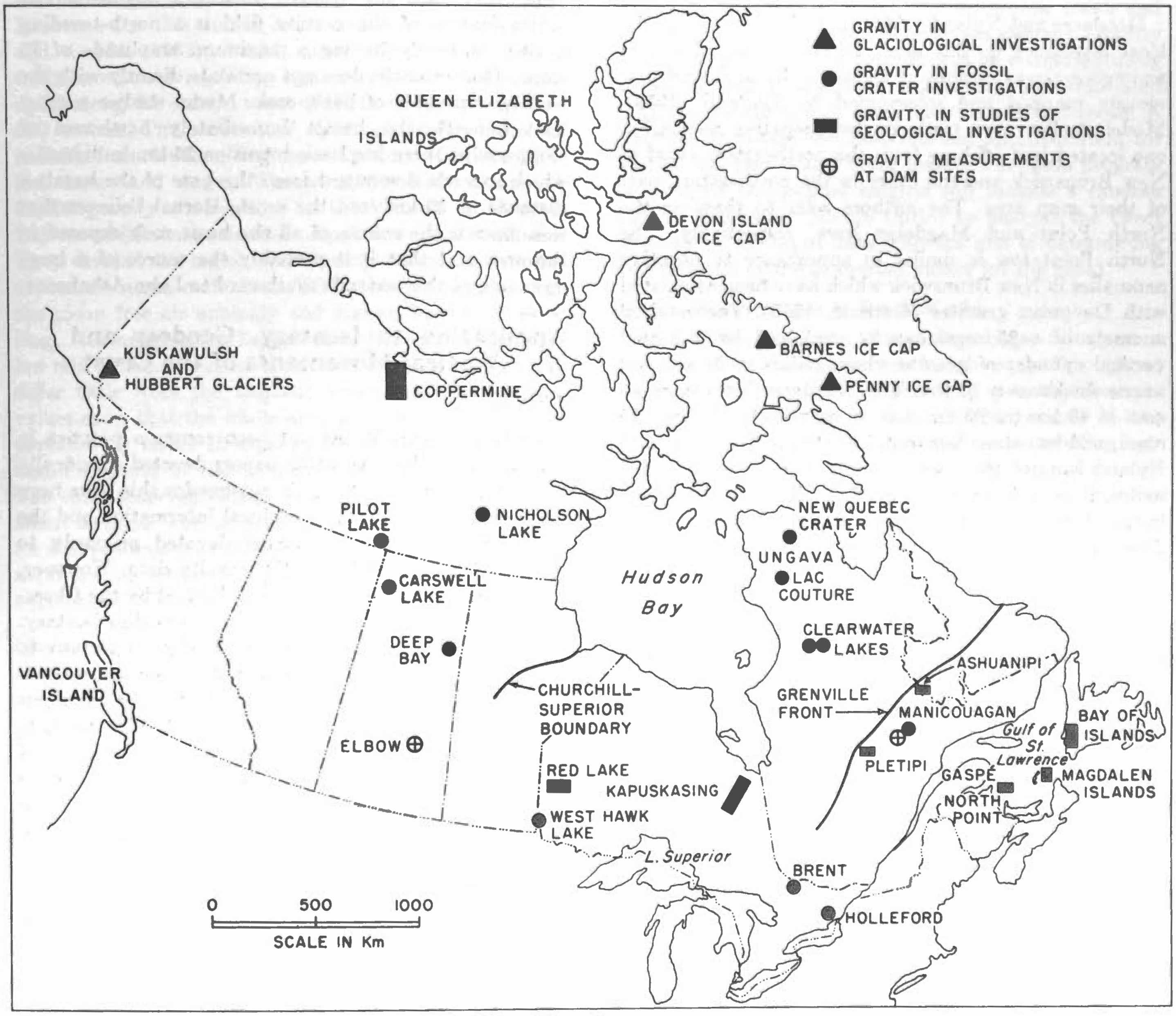

FIGURE 5. Index map for gravity investigations.

postulated by Rodgers and Neale (1963), they should be relatively thin and the gravity anomaly over them would be small. Generally this is true as the anomalies are less than 10 mgal over all but the North Arm Mountain intrusion where a 40 mgal positive local anomaly is observed. The model studies, based on the assumption that the intrusion is the source of the anomaly, suggest that the basic and ultrabasic rocks must extend to a depth of about 4 km to account for the anomaly at North Arm Mountain. This would appear to be rather thick for gravity sliding. Weaver concludes by stating that the gravity data do not refute the klippen theory, although the result at North Arm Mountain does cast doubt on it.

The Gulf of St. Lawrence

Goodacre and Nyland (1966) investigated some of the local anomalies in this area. In some cases the local anomalies are extensions of those on the mainland previously mapped and interpreted by Garland (1953). Model studies were made on two negative anomalies: one located just offshore from the northeastern coast of New Brunswick and the other in the northeastern part of their map area. The authors refer to these as the North Point and Magdalen lows, respectively. The North Point low is similar in appearance to negative anomalies in New Brunswick which have been associated with Devonian granites (Garland, 1953). The residual anomaly of −25 mgal can be explained by a buried vertical cylinder of granite whose radius is 20 km and whose thickness is 12 km. The Magdalen low covers an area of 40 km by 70 km, has an amplitude of about 25 mgal, and has steep horizontal gradients. Goodacre and Nyland suggest the source of the anomaly lies in the sedimentary column and postulate this source to be a buried lens of Mississippian sediments, possibly evaporites, 40 km wide and 3 km thick.

Western Ontario

Grant, Gross and Chinnery (1965) have carried out a gravitational study of the Red Lake greenstone belt, which is one of a number of such belts located in the Superior Province of the Canadian Shield. It is a fairly typical greenstone belt, being composed of a complex assemblage of lavas, sediments and intrusions. The belt is surrounded, and therefore completely isolated from other greenstone belts, by granitic batholiths and acid paragneiss. Generally speaking, greenstones are more dense than the surrounding granitic rocks and therefore they result in relatively positive gravity anomalies, the gradients and amplitudes of which give some indication of their shape and over-all thickness.

At Red Lake, the greenstone belt is 35 miles long by 18 miles wide. Analysis of gravimetric observations taken across the width of the belt indicates that it tapers sharply with depth to a maximum thickness of approximately 8 km. The authors conclude by stating that the results of this work appear to confirm, as most geologists feel intuitively, that greenstone belts are basin-shaped and are underlain by granitic batholiths and gneiss. A similar result was found in an earlier study by Innes (1960) who calculated, from gravity data, that greenstone belts in the Red Lake and Kenora-Rainy Lake districts extended to depths of 4 and 6 km, respectively.

Northwest Territories

Hornal (1966) presents and interprets the results of a gravity survey covering an area of 100,000 km^2 in the Canadian Shield south of Coppermine on Coronation Gulf. The map area includes the Proterozoic Coppermine basalt flows and the Muskox ultrabasic intrusion. The major feature of the gravity field is a north-trending positive anomaly having a maximum amplitude of 75 mgal. This anomaly does not correlate directly with the surface exposures of basic rock. Model studies suggest that beneath the basalt immediately northwest of Coppermine there is a basic intrusion 25 km in diameter which extends downward from the base of the basalt a distance of 20 km into the crust. Hornal believes that this mass is the source of all the basic rock exposed in the area and that it is probably the source of a large dyke swarm that extends southward to Lake Athabasca.

Application to Isostasy, Geodesy and Vertical Movements of the Crust

Isostasy

In recent years it has not been common practice in Canada to produce scientific papers devoted specifically to isostatic studies. The main reasons for this have been the lack of adequate topographical information and the urgent requirements for papers devoted primarily to geological interpretation of the gravity data. However, many papers, particularly those published by the Observatory, do contain some brief remarks regarding isostasy. These are not reported here. It is also important to recall that the regional correlation of gravity and seismic data described previously have a definite bearing on our concepts of isostatic compensation. Results to date indicate that the Pratt as well as the Airy theory of compensation must be considered. In the near future seismic experiments will be conducted in the Canadian Shield. The joint interpretation of the gravity and seismic data in this region will undoubtedly lead to important isostatic investigations.

Isostasy in the Canadian Cordillera. Elsaharty and Grant (1965) made a series of gravity observations along a traverse through the Canadian Cordillera close to the border with the United States. The measurements were made at 3- to 4-mile intervals. The isostatic reduction and interpretation of these measurements indicate that compensation beneath the Cordilleran massif is regional rather than local. Using the Vening-Meinesz tables, the values found for T (mean crustal thickness) and R (radius of regionality) were 30 km and 115 km, respectively. These values imply a mean crustal rigidity that is comparable in magnitude to those determined from seismology and from postglacial rebound.

Hughson (1965) has correlated Bouguer gravity, elevation and crustal thickness along a profile which extends from the plains region into the Cordillera. It is based on data from various sources.

Isostasy and Crustal Uplift in the Central Canadian Shield. Hudson Bay is believed to have been a locus of maximum glacial loading during the recent ice age. Evidence for this comes from isobase maps (Farrand and Gajda, 1962), based upon elevation of raised beaches without regard to age, which show the recent uplift along the eastern coast of Hudson Bay to be about 300 metres. The amount of uplift generally decreases radially from Hudson Bay for a distance of about 1000 km. Innes and Argun Weston (1966) have examined 50,000 gravity observations in the vicinity of Hudson Bay for additional evidence in support of this hypothesis. They divided the region surrounding the bay into three concentric zones, each about 300 km wide, and computed the mean free air anomaly and station height for each ring. The mean station heights show the area to be one of low relief which indicates that the free air anomalies will differ little from the isostatic anomalies. These mean values show that the whole area appears to be overcompensated by about 15 mgal and that there is a definite negative trend in the anomalies toward Hudson Bay. The total observed change in mean free air anomaly is about 25 mgal. The authors suggest that this is evidence for a hypothesis that Hudson Bay was a centre of maximum ice accumulation and also suggest that isostatic adjustment following deglaciation may be incomplete.

Geodesy

The Dominion Observatory has continued its program of applying measurements of gravity to problems of geodesy. This work is divided into two parts:

1. The determination of the geoid over Canada.
2. The study of local variations of the geoid.

Recently the emphasis has been placed on the former and Dr. Nagy has made excellent progress in the development of a computer-based method to determine the geoid in Canada. The computations, which require gravity values over the earth, will be based on surface measurements of gravity by the Observatory within Canada and on gravity values calculated using published coefficients of spherical harmonics from satellite observations for areas outside Canada. Progress to date with the computer programming indicates that preliminary determinations of the geoid in Canada should be possible in late 1967. The study of local variations of the geoid is a continuation of earlier work (Nagy, 1963) in which plumbline deflections computed from gravity data were combined with astrogeodetic deflections. The remainder of this section is devoted to a brief description of the computer programs developed to determine the geoid in Canada.

For areas within Canada a program has been written to fit surfaces of various degrees to the measured gravity values since it is not convenient to use the individual values of the gravity anomalies. Parameters to the program are the size of the surface elements and the degree of the polynomial necessary to fit the data. The program will determine the integral mean, the arithmetic mean and the standard deviation for each surface element. Gravity values for areas outside Canada will be computed using a program which generates, recursively, the Associated Legendre function, P_n^m, using fully normalized forms. A program to obtain the best rational approximation for Stokes' function is also being tested. The main program to compute the geoidal heights will include a random number generator (Monte Carlo) to analyze the effect of errors in the input data with the aim of determining uncertainties of the computed values for the geoid.

Gravity Measurements at Bench Marks

In 1964 the Dominion Observatory began a long-term program to measure gravity at bench marks throughout Canada. This work is intended to provide accurate gravity values for gravimetric determinations of the geoid and for the adjustment of the precise levelling network, and to provide points of control for detailed gravity surveys for crustal studies. The project also includes measurements in the vicinity of dam sites currently under construction. These measurements will be repeated periodically in the future to study the effects of the increased load on the crust due to the water. All the observations are being made at bench marks and other monumented sites. Thus far measurements have been made at large dam sites in the Provinces of Quebec and Saskatchewan.

The Geodetic Survey of Canada has been reobserving some of their level lines for evidence of differential vertical movements of the crust. Preliminary analysis of some data in southern Quebec has recently been completed. This work is reported by Lilly (1967).

Application to Glaciology

Penny Ice Cap, Baffin Island, N.W.T.

In connection with the Hydrological Decade a long-term project was initiated by the Dominion Observatory under the direction of Dr. J. R. Weber in 1962 to measure fluctuations of the surface elevation of the Penny Ice

Cap by the gravimetric method. A double line of aluminum poles, 9 km long, was established across the crest of the ice cap. The two lines were 1 km apart and the individual poles of each line 1.5 km apart. The lines were tied to permanent markers in bedrock by tellurometer-triangulation. Simultaneous reciprocal vertical angles were observed between poles to establish reliable elevation differences. Gravimeter observations were made between the 14 poles and "Gravity Base" located on a rock outcrop. Fifteen ablation stakes were also installed across a major outlet glacier and the down-glacier and cross-glacier movement was measured. Ice thicknesses across the crest of the ice cap and along the movement line across the outlet glacier were also determined seismically.

In 1965 a complete resurvey was carried out. Very little horizontal movement was observed. In addition gravity, radar and electric depth determinations were made on profiles across and along the major outlet glacier. The radar equipment, a SCR-718F 400-mc altimeter on loan from the RCAF, was operated from a Nansen sledge pulled by a Snowbug. This equipment could be used for depths of 500 metres or less.

In 1966 the gravity measurements between the 14 poles across the crest and "Gravity Base" were repeated. The gravity change along the direction of movement of the centre pole was also observed. Stratigraphic snow analysis, density and temperature measurements were also carried out at the centre (elevation 1838 metres above mean sea level).

Dr. Weber is preparing a complete report on this project.

Barnes Ice Cap, Baffin Island, N.W.T.

The Dominion Observatory, in 1962, carried out a combined gravimetric and seismic study of this ice cap. The observations were carried out along a SW-NE traverse across the crest of the ice cap. Bamboo poles were drilled into the ice at 1-km intervals and accurately surveyed relative to monuments established on land at either end of the traverse.

Devon Island Ice Cap, N.W.T.

During 1962, as part of the Arctic Institute of North America's Devon Island Expedition to the Canadian Arctic, gravity traverses (Hyndman, 1965) were made on the western end of the Devon Island ice cap to determine ice thickness and bedrock topography. Hyndman's interpretation of the gravity data indicates the ice cap probably has a rock core and that thickness of ice is generally less than 500 metres. The depths quoted are estimated to be within 15 and 20 per cent of the true values on the ice cap and outlet glacier, respectively.

Ice Field Ranges, Yukon Territory

Clarke (1966) carried out seismic and gravity observations across the Kuskawulsh and Hubbert glaciers near Kluane Lake. The glaciers are joined together and the geophysical observations were used to locate the divide between them.

Melville Island Ice Caps, N.W.T.

Spector (1966) determined the thickness and volume of four ice caps located on Melville Island. These ice caps, which all have diameters of 15 km or less, occur in an area where the regional gravitational field is apparently very smooth and the bedrock geology uniform. This is a fortunate circumstance because the interpretation of the gravity data is simplified in comparison with the usual glaciological problem. Generally, Spector found the ice caps to be relatively thin; the greatest thicknesses calculated, using the Bouguer hypothesis, ranged from 30 to 50 metres over hidden valleys or depressions under the main, or largest, ice cap. Ice cap volumes ranged from 0.2 to 1.0 km^3.

Application to Fossil Crater Studies

Since the intensive investigation of circular features of possible meteoritic origin began at the Observatory in 1953, several dozen such features have been investigated. Twelve on the Canadian Shield have been identified as probable meteorite craters on the grounds of structure and shock deformation. Of the twelve structures, ten have been subject to gravity, eight to magnetic and five to seismic surveys while six have been drilled. In all cases negative Bouguer gravity anomalies have been detected, although in some instances the anomaly due to the crater has been obscured by strong regional gradients.

Typical negative anomalies were recorded at Holleford, Brent and Deep Bay in the early stages of these investigations and were reported in Millman, *et al.*, (1960); Beals, (1960); Innes, (1961); Beals, Innes and Rottenberg (1963); Innes, *et al.*, (1964). Subsequent drilling at all three craters showed that the anomalies were due to the combined effects of sedimentary fill of Palaeozoic or Mesozoic age and underlying breccia. Relatively complete drilling results at Brent enabled Innes (1961) to show that virtually all the anomaly had been accounted for in the section penetrated.

Halliday and Griffin (1963) made a similar study of West Hawk Lake in 1959 and 1962 and their analysis detected a 6 mgal negative anomaly over the lake despite the obscuring effects of a 28 mgal change in regional anomaly across the lake. Drilling in 1965 and 1966 confirmed the presence of low-density sediments underlain by over 1000 feet of breccias under the lake. As at Brent, the measured anomaly could be accounted for by the low densities of the sediments and breccia cored (Halliday and Griffin, 1963, 1966, 1967).

Gravity and topographic measurements made at the New Quebec crater have been presented in preliminary form by Innes (1964). A residual negative Bouguer anomaly of 6 mgal remains after corrections for water and terrain. A final terrain correction is in preparation. The results agree with those for the Brent crater, which is of similar size.

The gravity fields over large craters (more than 10 km across) have been measured at Carswell (Innes, 1964), Clearwater Lake (Dence, 1964, 1965; Dence, *et al.*, 1965), Nicholson Lake (Innes, *et al.*, 1967) and Manicouagan. Drilling has been carried out at the Clearwater craters in 1963 and 1964. The anomalies at Carswell and Manicouagan are obscured by strong regional gradients but in every case negative anomalies of 7 to 13 mgal have been recorded. These are somewhat less than would be expected from extrapolation of the results from the smaller craters. The difference can be attributed to the presence of central uplifts and attendant structural changes in the large craters when compared with the simple smaller ones. The large craters also have suffered more erosion than the smaller ones, and except in the case of East Clearwater have no protective sedimentary cover. However, it is unlikely that erosion alone can account for the change in character of the anomalies.

Recent studies of shock metamorphism as found at the Canadian craters (Dence, 1967; Robertson, *et al.*, 1967; Bunch, *et al.*, 1967, in press) show that shock up to about 100 kilobars pressure makes little difference to rock densities or other physical properties. The most important influences are brecciation and fracturing following passage of the shock wave. These later effects are controlled by the geometry of the crater and involve both strongly and weakly shocked rocks. Indeed much of the gravity anomaly is due to weakly shocked rocks of the crater rims slumping into the crater as incoherent but virtually monomict breccias. Further analysis of geophysical measurements at craters which have been drilled are proceeding in the light of these data.

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