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NOTE:
Page 385, *delete* line 15 and substitute:

$$\log v_u = \frac{1}{k+1}(\log a - k \log \alpha). \qquad (8)$$

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CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
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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.
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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.

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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^2
(National Reference Station)

WASHINGTON......................... 980.1192 cm/sec^2.
(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.

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

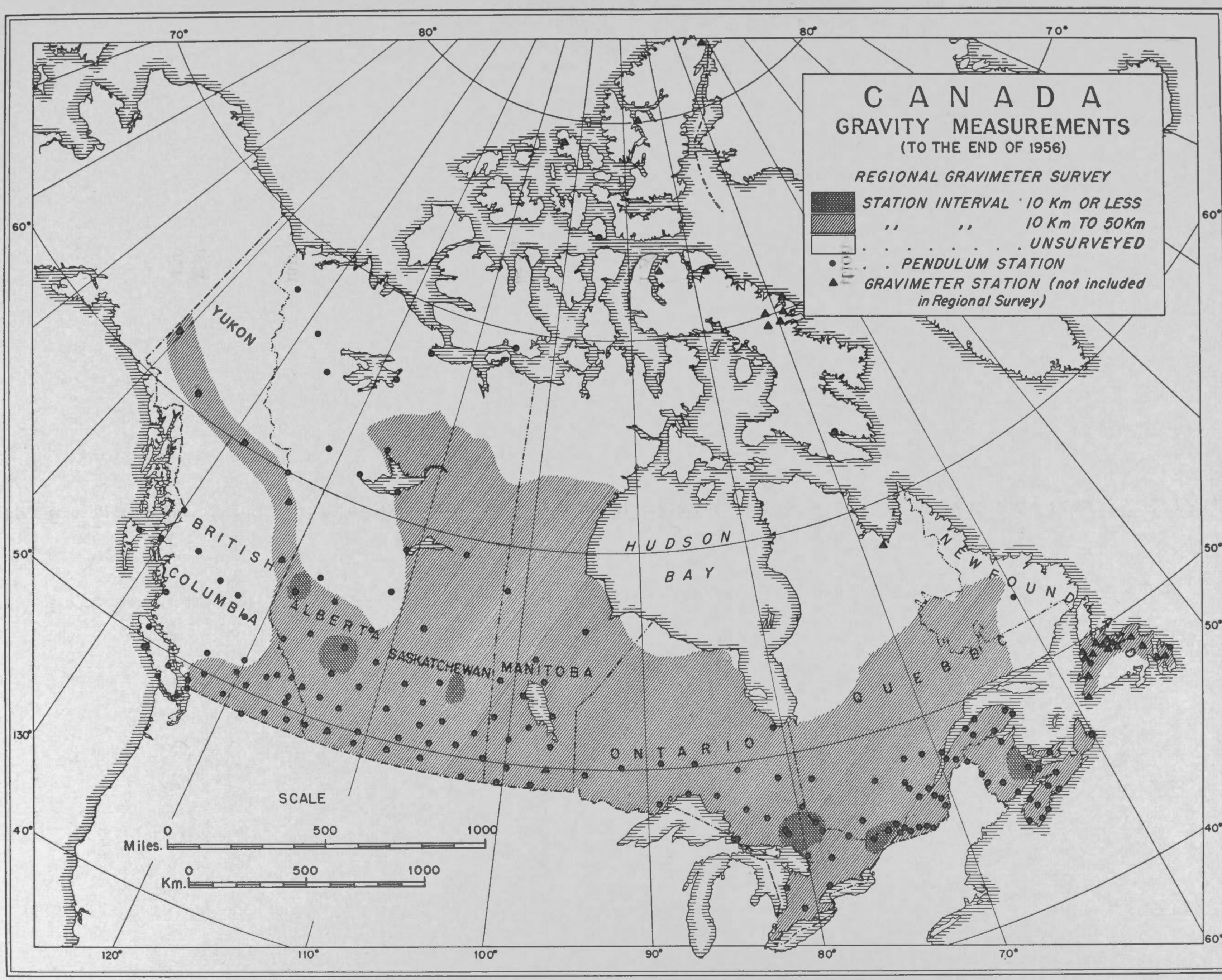

Fig. 2. Gravity measurements in Canada to the end of 1956.

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 × 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 8½ 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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A THREE-COMPONENT AIRBORNE MAGNETOMETER

BY

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AND

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CONTENTS

CONTENTS—Concluded

A Three-Component Airborne Magnetometer

BY

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ABSTRACT

A three-component airborne magnetometer has been designed and built at the Dominion Observatory. The magnetometer is mechanically linked to a gyro-stabilized platform which is maintained horizontal, independent of the motions of the aircraft. The gyroscopes are precessed at a rate proportional to the time integrals of signals from accelerometers mounted on the platform. The system acts basically as a pendulum with a six-minute period. Damping is provided by phase-advance networks in the control loops. Forced oscillations of the platform are reduced by the addition of automatically computed signals proportional to the aircraft accelerations. The accuracy of the platform is 2 or 3 minutes of arc under normal survey conditions. The azimuth reference for the instrument is provided by a directional gyroscope mounted on the platform, whose drift is determined to an accuracy of 0.2° by astronomical measurements with a periscopic sextant stabilized in azimuth.

The magnetometer head contains three orthogonal magnetic detectors of the saturated transformer type, which give direct currents proportional to the fore-and-aft and transverse horizontal components and the vertical component. These and the heading of the aircraft are fed into an analog computer which displays continuously the declination in degrees, and the horizontal and vertical field components in gauss. An alternative display presents automatically the average values of these quantities over successive five-minute intervals. The accuracy of measurement of field components referred to the reference axes established by the stabilization system is estimated to be 0.1° in declination, and 20 gammas in the other components.

Sources of error in survey operations are discussed and the reduction of survey results and the determination of the corrections for the magnetic field of the aircraft described. It is concluded that the probable error of a survey observation as plotted on a chart is about 100 gammas in any component, and is principally due to errors in navigation and plotting.

INTRODUCTION

Magnetic charts showing the direction and intensity of the geomagnetic field have been prepared for over a century from observations made at points scattered over the earth's surface. The distribution of the magnetic stations on land, while it is generally adequate in well-developed areas, is often quite inadequate in others, such as the Arctic and Antarctic. Over the seas, which cover two thirds of the earth's surface, no important magnetic surveys have been made since the loss of the specially constructed ship *Carnegie* in 1929. The absence of recent observations at sea is especially serious, since the rate of change of the geomagnetic field is not constant, and extrapolation of earlier results over 25 years has undoubtedly resulted in large errors in the present world charts (1,2).

The success of the airborne total-intensity magnetometer in geophysical prospecting suggested that an airborne instrument capable of measuring the direction of the geomagnetic vector in addition to its intensity would improve greatly the reliability of magnetic charts for most parts of the world, and would be particularly useful in northern Canada. Airborne magnetic observations have the following advantages over measurements made by standard methods:

(*a*) observations can be made with one instrument and one technique over land, sea, or ice;

(*b*) large scale surveys of the accuracy required for the usual charts can be made more quickly and at less expense;

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(*c*) airborne measurements are virtually unaffected by local anomalies which can make observations at an isolated ground station useless for mapping purposes;

(*d*) an airborne magnetometer can produce continuous profiles of the magnetic components, which help the map-maker to decide which anomalies should be indicated on a particular map, and may reveal interesting geological features;

(*e*) aircraft are by nature less magnetic than other practical vehicles.

The main difficulties in making airborne magnetic measurements are:

(*a*) the establishment in a moving aircraft of an accurate direction reference system with respect to which the direction of the magnetic vector is measured;

(*b*) the problem of establishing the geographical location of the observations;

(*c*) the necessity of either compensating the magnetometer or correcting the observations for the magnetic field of the aircraft.

Two basic considerations governed the over-all design of the magnetometer. First, the instrument was to present magnetic results in a form as close as possible to that required for the preparation of magnetic charts, in order to avoid the necessity of a large staff for the processing of data. It was decided that the instrument should indicate the declination, the horizontal component and the vertical component, and that the indicators should show the three quantities directly in the usual units—degrees and oersteds. The second aim was that the accuracy of measurement should be 0.1 degree in declination, 10 gammas (10^{-4} oersted) in the horizontal component and 10 gammas in the vertical component.

From the first requirement, it was apparent that the direction reference system should be that defined by the vertical and geographical north (rather than one defined by the direction of two stars, for instance). The second aim required that the direction reference system be accurate to one minute of arc in the determination of the vertical and 0.1 degrees in azimuth. When the project was begun, the accuracy to be expected from available gyro-vertical systems was of the order of one degree. The success of this project, therefore, depended on the development of an improved system for the determination of the vertical in an aircraft.

In its broadest outline, the three-component airborne magnetometer consists of a field-measuring device mounted on a horizontal gyro-stabilized platform inside the aircraft. The role in the over-all design of the instrument of the first requirement stated above may be seen by comparing the Caandian instrument with the airborne magnetometers developed by American and British groups to measure the intensity anddirection of the earth's field.

The instrument developed in the United States—The Vector Airborne Magnetometer—has been described by Schonstedt and Irons (3). The total intensity is measured with a detector aligned in the total field, and the angles between the axis of the detector and a reference system, defined by a damped pendulum and the astronomically determined heading of the aircraft, are continuously recorded. After these angles have been averaged over a suitably long period of time, they are used to compute the components of the magnetic field with the aid of I.B.M. machines. The apparatus is relatively simple, but operation is limited to high altitudes (20,000 feet) where flying conditions are smooth, and the accuracy of measuring the magnetic field in the aircraft is probably an order of magnitude less than that considered above.

The British development (4) proposes to measure the total field and the component in the direction of the sun. A second flight, when the sun has changed position, supplies a third component. The apparatus should be nearly an order of magnitude more accurate than the Canadian instrument, but it can be used only when the sun is visible and Decca navigation is available. An electronic computer is used to convert the information to a useful form.

Although the accuracy of the present three-component magnetometer approaches the design accuracy (0.1° in declination, 10 gammas in the horizontal and vertical components) in measuring the magnetic field at the magnetometer head, its accuracy in measuring the geomagnetic field is considerably lower because of uncertainties in the corrections applied to the readings for the magnetic field of the aircraft. It is shown in Part 3 of this report that these uncertainties amount to 60 gammas in the horizontal vector and 30 gammas in the vertical component. In making geomagnetic observations on the ground, it has been customary to try for an accuracy of one gamma in three orthogonal components, which has made possible the investigation of diurnal variation and secular change. A sensitivity of 10 gammas is usually adequate in magnetic prospecting. It is thus necessary to consider the usefulness of geomagnetic measurements with a lower order of accuracy, such as are obtained with this instrument.

The amount of detail that can be shown on a magnetic chart depends on the scale—charts covering Canada at a scale of 100 miles to the inch usually show contours of the components at 1000-gamma intervals. The magnetic components at a point can be read to within 100 gammas. In drawing the contours the magnetic data must be smoothed, the degree of smoothing depending on the geographical density of observations and the geology of the area. In the case of the 100-mile-to-the-inch charts, an analysis of the differences between values read from the completed charts and the original ground observations used in their preparation showed that the smoothing produced probable deviations of two or three hundred gammas.

It is concluded that the accuracy of the three-component airborne magnetometer is sufficient for the production of charts on a scale of 100 miles to the inch, and is probably satisfactory for charts covering smaller areas, at 20 miles to the inch.

In computing and plotting airborne observations, considerable time is saved by accepting an accuracy of 50 gammas. It is usually unnecessary to correct the observed values for diurnal variation and magnetic disturbances; such corrections, in any case, can be made only in areas well supplied with magnetic observatories.

In order to facilitate the plotting of results, an automatic averaging system has been included in the present magnetometer. This device computes automatically, during flights, the average values over successive 5-minute periods of time, of the declination and the horizontal and vertical components. When observations are plotted to 50 gammas, it is usually sufficient to plot only the average values (corresponding to averages over 20-mile segments of the magnetic profiles) and a great saving in office work is achieved.

This report on the three-component airborne magnetometer is divided into three parts. The method of establishing the directional reference system and the method of making magnetic measurements with respect to that system are treated separately in Parts 1 and 2. Part 3 discusses the accuracy of the instrument as a whole, with emphasis on the correction of observations for the magnetic field of the aircraft, and presents experimental results obtained in 1953 and an analysis of a survey of western Canada made in 1955.

The instrument described in the present paper was designed and built between 1951 and 1955 at the Dominion Observatory. One of the authors (S.Z.M.), who worked on the project until the end of 1952, was on the staff of the Defence Research Board. This paper is substantially a revision of an earlier report by the three authors written in 1954; this earlier report, D.R.B. D-45-31-30-02, 1955, was classified SECRET until November 1956. It is not intended as an account of the whole project, which dates from 1946, but as a description of the instrument in its present state of development together with results from recent surveys. Since many organizations have taken an active part in the project, particularly in its early stages, it is felt that a short history of the project should be given here.

The Universal Airborne Magnetometer Project was first placed on the program of the Subcommittee on Navigation of the Associate Committee on Aeronautical Research of the National Research Council of Canada at its third meeting on January 15, 1946. This Subcommittee was later succeeded by the Navigation Research Panel of the Defence Research Board of Canada, and the project was taken over by the new panel. These organizations have supported the project by annual grants from 1948 to the present. In the early years of its history there was considerable doubt as to the wisdom of carrying out this development in Canada, and it required pressure by the Subcommittee to keep the project active.

In 1947 W/C D. A. MacLulich, R.C.A.F., submitted to the Subcommittee a plan for a universal airborne magnetometer. This plan included an important feature which distinguishes this development from those in other countries—a gyro-stabilized horizontal platform on which is mounted the field-sensitive head of the magnetometer. The detailed design and construction of such an instrument began in 1948. W/C MacLulich, at the Central Experimental and Proving Establishment, R.C.A.F., (C.E.P.E.), undertook the construction of a gimbal-mounted platform maintained horizontal by two servomotors controlled by a vertical gyroscope. An automatic sun-compass, employing photo-electric cells to follow the sun, which was to supply the azimuth reference to the system, was developed under the direction of W/C MacLulich by the Photographic Survey Corporation in Toronto. A group working in the Department of Physics, University of Toronto, was to develop the equipment for measuring the components of the magnetic field.

A preliminary model of the stabilized platform, controlled by a war-surplus vertical gyroscope, was built by C.E.P.E., but was never tested in the air. A theoretical investigation soon showed that no commercially available vertical gyroscope would be nearly accurate enough, and the University of Toronto group designed a completely new gyroscope control system. A model of the system was built at the Dominion Observatory. C.E.P.E. constructed the servo-controlled platform to be operated from signals supplied by this system.

The first model of the airborne magnetometer, which was completed in 1950, is described in references 6 and 7. The complete instrument was flown only once, but the vertical gyroscope system was flown several times, furnishing valuable records of the long-period accelerations of the aircraft. These experiments showed that elaborate gyro-control systems were practical for survey work, and also that the theoretical accuracy of such a system would be approached only by a platform of careful mechanical design, using the best gyroscopes available. The automatic sun-compass was found to require almost perfect weather for successful operation, and it was abandoned in favour of the more flexible combination of a manually operated sextant and a directional gyroscope. Although the instrument which is the subject of this paper bears little resemblance to the 1950 model, its design is based on information obtained and lessons learned in the operation of the earlier equipment. The authors are thus greatly indebted to the organizations which took an active part in the early developments, and particularly to W/C D. A. MacLulich.

PART 1
THE GYRO-STABILIZED PLATFORM

1.1 INTRODUCTION

The three-component magnetometer consists of two main groups of components. The first group consists of a stabilization system which is described in Part 1 of this paper and which keeps a platform horizontal and furnishes a reference direction of known true azimuth. The other group of components is described in Part 2 of this paper and comprises the magnetometer, which measures the magnetic declination and the vertical and horizontal components of the magnetic field.

The platform is maintained horizontal, independent of the rolling and pitching of the aircraft, by two servo-motors controlled by error signals from a roll and pitch gyroscope mounted on the platform. The natural frequency of these servo systems is of the order of 30 cycles per second. The gyroscopes used are the Minneapolis-Honeywell HIG units.

Also mounted on the platform are two Minneapolis-Honeywell accelerometers, one for transverse accelerations and one for fore-and-aft accelerations. Signals from these accelerometers are integrated and modified by suitable error-rate stabilization networks before being applied to the precessing torque motors on the roll and pitch gyroscopes. In this way the direction of the normal to the platform is made to coincide with the average position of the apparent vertical in the moving aircraft, the time of averaging being longer than the periods of the accelerations found in a moving plane.

Basically the platform acts as a damped pendulum with a period of six minutes (equivalent length of a simple pendulum is about 20 miles). The natural period of the system must be long for good filtering characteristics, but cannot be made too long because of the time taken for transient recovery of the platform. A period of about six minutes seems a good compromise between good filtering with poor transient response and poorer filtering with better transient recovery. Using a six-minute period, accelerations of the aircraft with an amplitude of one degree deflection of the apparent vertical (0.02g) and a period of one minute will force an oscillation of the platform with an amplitude of about two minutes of arc and the same period. It should be pointed out that the method of damping does not introduce effects due to the rolling or pitching of the aircraft.

In order to reduce the amplitude of forced oscillations of the platform due to long-period accelerations of the aircraft, an attempt is made to reduce the periodic part of the input to the integrators by subtracting from the accelerometer signals, automatically computed signals proportional to the aircraft accelerations. The computed fore-and-aft signal is the derivative of the output of a true airspeed meter, and the computed transverse acceleration signal is the product of airspeed and the rate of change of heading of the aircraft. The heading of the aircraft is obtained from a third HIG unit mounted on the stabilized platform and used as a directional gyroscope.

In order to reduce transients following large changes in heading of the aircraft, torques proportional to earth's rate are applied to the roll and pitch gyroscopes. A small Coriolis correction is applied to the roll accelerometer output.

This part of the report contains a description of the gyro-stabilized platform, the gyroscopes used, and an outline of the mechanical design of the platform. The theory of the high frequency platform servoamplifiers is briefly discussed, and the theory of the long period gyroscope erection systems fully described. The circuits required to operate and control the platform are described, and the initial alignment procedures mentioned. The synchronous periscopic sextant, used to determine the corrections to be applied to the directional gyroscope, is briefly described. Finally, the performance of the platform in flight is illustrated from field records.

1.2 GENERAL DESCRIPTION OF THE GYRO-STABILIZED PLATFORM

1.2.1 *The Platform*

Plate I shows the stabilized platform and magnetometer head. A wooden box bolted to the floor of the aircraft carries four shock-mounts Q. The shock-mounts support a rectangular wooden frame F, to which is bolted the outer gimbal ring E. The inner gimbal C can rotate about the longitudinal axis of the aircraft (the roll axis) in bearings set in gimbal E. The gyroscope platform A is supported by bearings in gimbal C which allow it to rotate about the pitch axis—an axis perpendicular to the roll axis.

The magnetometer yoke N is rigidly connected to the inner gimbal C by an aluminum pipe H. The yoke supports a small platform on two bearings which define an axis parallel to the pitch axis of the gyroscope platform. The magnetometer head G is mounted on the small platform. The magnetometer platform is mechanically connected to the gyroscope platform by a linkage parallelogram whose lower arm can be seen at J. In this way the planes of the two platforms are parallel independent of the attitude of the aircraft.

The gyroscope platform A is maintained steady in space, when the aircraft rolls or pitches, by the roll servomotor D and pitch servomotor B, which apply torques to platform A about the roll and pitch axes respectively. The signals controlling the servomotors originate in two gyroscopes, the roll and pitch gyros, fixed to platform A.

A third gyroscope K is mounted to a turntable L, which can rotate about a vertical axis in bearings carried by the platform A. A third servomotor is controlled by gyroscope K so as to maintain constant the azimuth of the turntable when the aircraft yaws or changes heading. Thus K functions as a directional gyroscope, and an angle measuring system measures the aircraft heading relative to this directional gyroscope.

The operation of the servo loops can be understood as follows. When, for instance, the aircraft rolls, friction in the gimbal bearings causes the platform to roll. Immediately, the roll gyroscope gives an electrical signal proportional to the angle through which the platform has rotated, and the roll servomotor applies a torque to the platform in the sense opposite to the torque disturbing it. For the platform to be steady to one minute of arc, the motor must develop a large torque for a small angular displacement of the platform, and the loop gain of the servo system must therefore be very large. The result is a servo system with a high natural frequency and a stability problem of considerable difficulty. The following conditions must be fulfilled:

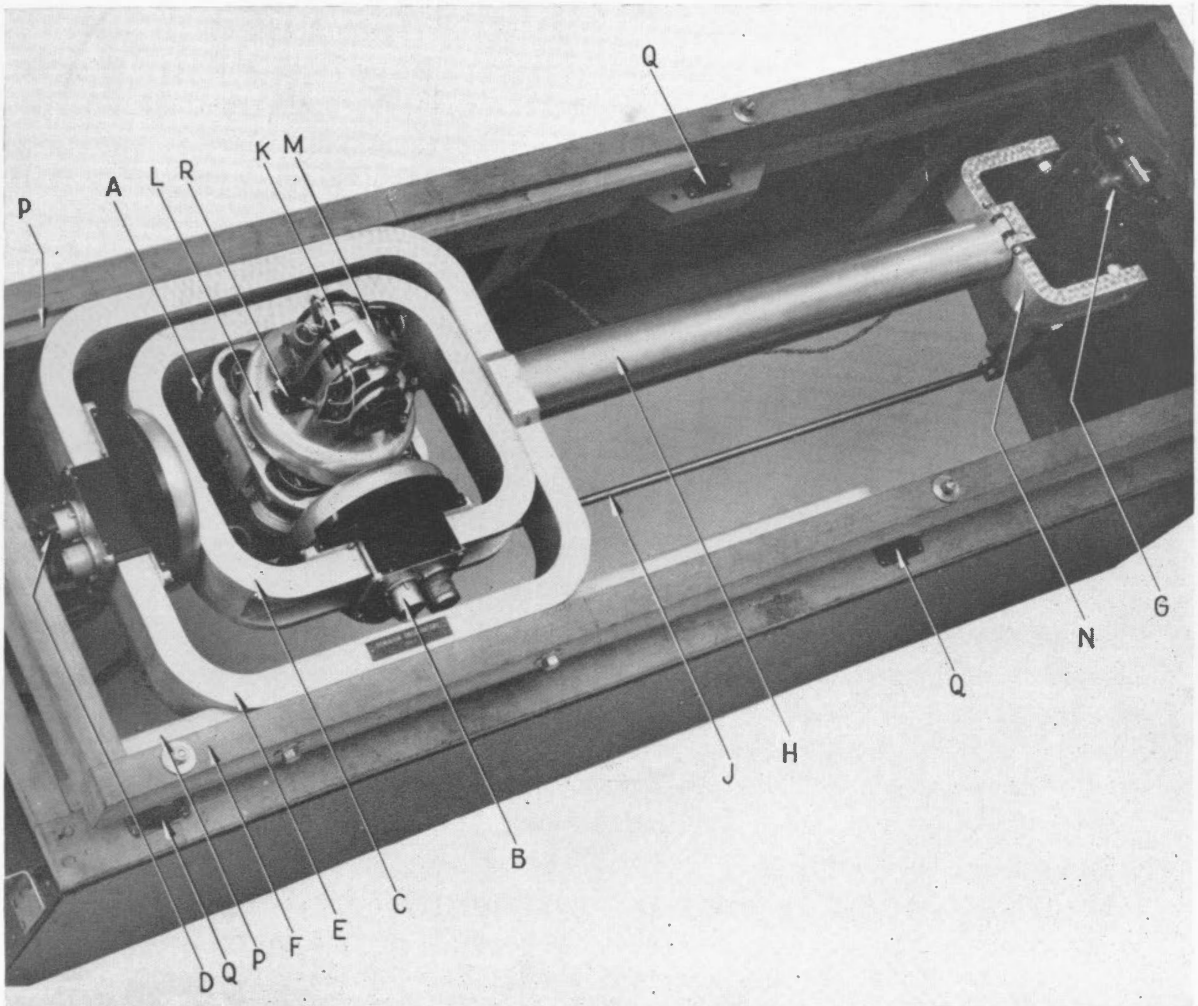


PLATE I—The gyro-stabilized platform and magnetometer head

(*a*) the gyroscopes must have a low threshold, i.e. they must give a useful signal for an angular displacement of a fraction of a minute of arc;

(*b*) the gimbal system and gear trains must be rigid, with natural frequencies much higher than the natural frequency of the servo loops;

(*c*) backlash in the gimbal bearings and gear trains must be negligible;

(*d*) damping of the servo loops must be of the error-rate type in order to avoid velocity errors of the platform when the aircraft undergoes rapid angular motions.

While the system as described will maintain the platform steady in space for a short period of time, it will not hold the platform horizontal over a long period because of the unpredictable wander rates of the gyroscopes, the rotation of the earth and the velocity of the aircraft over the earth. For the long-term stability the gyroscopes must be controlled by applying precessing torques, which are determined automatically by a computer whose inputs are navigational information and signals from two accelerometers mounted on the gyroscope platform.

The design of the long-period control system is described later in section 1.5.

1.2.2 *The Gyroscopes*

The three gyroscopes are Minneapolis-Honeywell HIG-5 units, Type GG1A-2. The electrically driven rotor is sealed in a gimbal can, which rotates about its axis of symmetry or output axis, in jewelled bearings. The spin axis of the rotor is perpendicular to the output axis. A third axis perpendicular to both the spin axis and the output axis is known as the *input axis*. The gimbal can floats in a viscous fluid, which fills the gyroscope case and provides damping, and is thermostatted at 167°F.

When the gyroscope case is rotated about the input axis, the gimbal can rotates with respect to the case about the output axis. The viscosity of the fluid is chosen to make the output angle approximately equal to the input angle. The output angle is measured by a microsyn pick-off at one end of the gimbal can. At the other end of the can is a microsyn torque generator, which is used to control the equilibrium position of the gyroscope by applying torques about the output axis.

Using rigid heat-insulating clamps, the roll and pitch gyroscopes are clamped to the gyroscope platform with their output axes vertical and their input axes parallel to the roll and pitch axes respectively. The directional gyroscope is mounted on the turntable with its output axis horizontal and its input axis parallel to the axis of rotation of the turntable.

The chief reasons for the choice of HIG-5 units, in addition to availability and compactness, are the low friction levels and low thresholds obtained in these gyroscopes.

Extremely low friction levels are attained by the technique of floating the gimbal can which permits the use of small jewelled bearings on the output axis. Low friction results in an apparently random wander-rate which is low and consistent, considering the small size of the gyroscope. As will be shown in section 1.5, in this application a constant wander-rate in the platform gyroscopes is not important, but a steadily changing wander-rate causes a constant error in the determination of the vertical, and abrupt changes in wander-rate produce transient errors which persist for a long time. The changes in wander-rate recorded in bench-tests of the two platform gyroscopes in April 1952 were in the range 0.12 to 0.03 degrees/hour/minute and these changes were acceptably small. No sudden changes of rate were observed at this time. However, later tests on six units showed serious deterioration in performance after a few week's operation (section 3.6).

The microsyn pick-off on the output axis has a low noise level, and produces useful signals for angular displacements as small as 0.1 minutes of arc, without resorting to special circuit techniques. This low threshold is necessary for the short-term stability of the platform, as was mentioned in section 1.2.1.

1.3 THE MECHANICAL DESIGN OF THE STABILIZED PLATFORM

The aluminum castings used in the construction of the platform were supplied by the Mines Branch, Department of Mines and Technical Surveys, Ottawa, and the machining and assembly of the platform carried out in the machine shop of the Dominion Observatory.

The design of the component parts of the assembly is discussed below.

1.3.1. *The Design of the Platform Gear Trains*

The gear boxes of the roll, pitch and azimuth servo systems are identical in design. A ratio of 720 to 1 between the motor and the output shaft was chosen, allowing the platform to remain stationary for angular velocities of the aircraft up to 44°/second. In order to obtain zero backlash, each gear box includes two parallel gear trains, one of which is preloaded against the other by a single spring, as shown in Figure 1.1. Without spring-loading, the total backlash of the two gear trains amounted to about 10° at the motor shaft. The spring was wound up to produce a constant torque greater than the maximum torque of the motor reflected at the shaft in question (12 oz. in. in this design).

The gears and shafts are made from S.A.E. 62 bronze. The form of the gear teeth is American Standard Stub Tooth, 48 pitch and 20° pitch angle. The gears were cut by Precision Gear (Canada) Ltd. The large internal gears were made from a centrifugally cast bronze bushing (similar to A.S.T.M. B-139-44, Grade D) supplied by Montreal Bronze Company Ltd.

A basic aim in the design of the platform servo systems was that the loop gain should be of the order of 2×10^{11} dyne cm./radian, measured at the platform. The corresponding torque for a displacement of the platform of one minute of arc is 4 ft. lb. The moment of inertia J of the system, measured at the platform is 4×10^6 gm. cm^2. Very roughly, the natural frequency of the system is then

$$f_n = \frac{1}{2\pi}\sqrt{\frac{2 \times 10^{11}}{4 \times 10^6}} = 35 \text{ cycles/second.}$$

The angular compliance X of the gear train introduces another mode of vibration into the system with a natural frequency of the order of $f_g = \frac{1}{2\pi}\sqrt{\frac{1}{XJ}}$. In order that the servomechanism can be made stable, it is necessary that $f_g \gg f_n$, that is $X \ll 5 \times 10^{-12}$ radians/dyne cm.

In designing the gear trains, an attempt was made to estimate X using the methods shown in Appendix I.

$$X = X_t + X_d + X_g + X_b \quad \text{, where}$$

X_t is the compliance due to torsion in the shafts,

X_d is the compliance due to bending in the shafts,

X_g is the compliance due to deflection of the gear teeth, and

X_b is the compliance due to radial deflection of bearings.

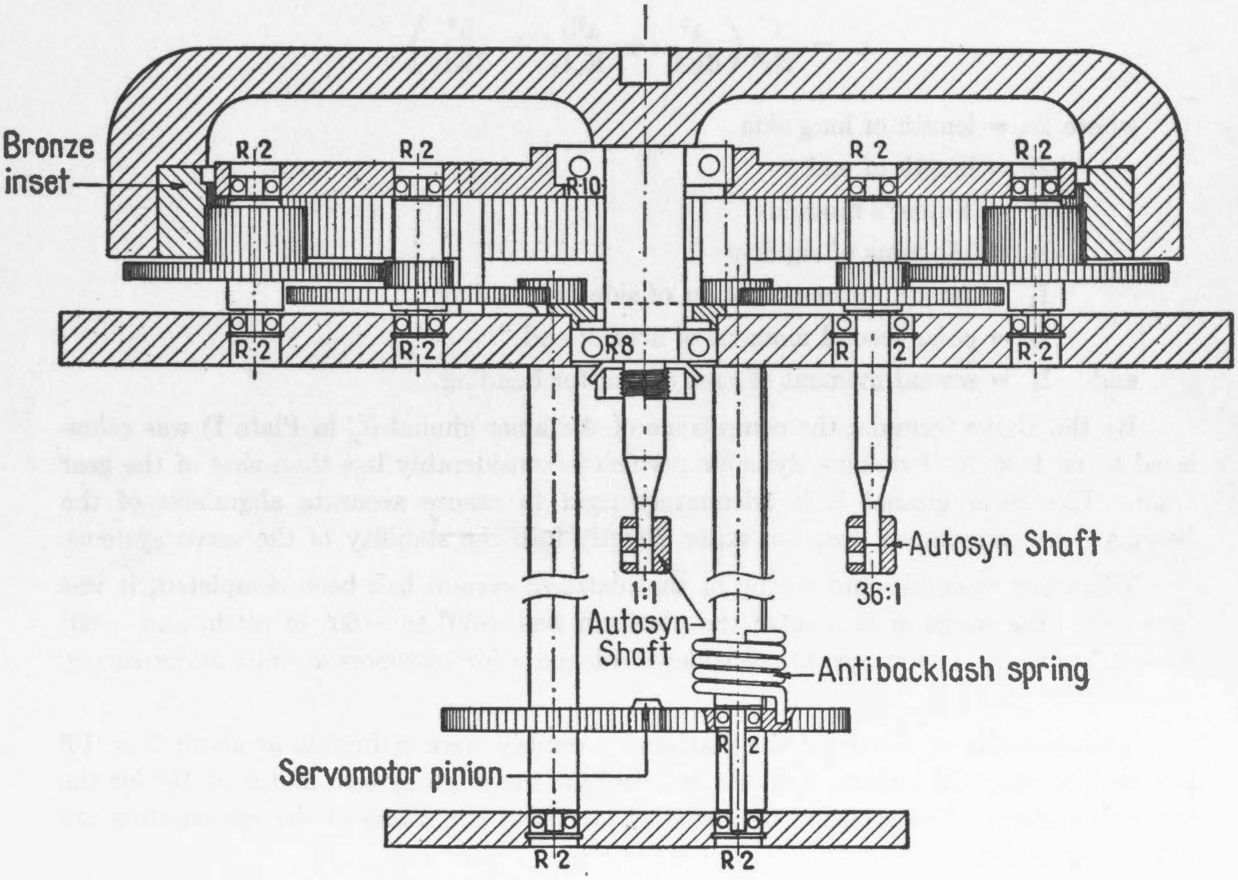
The following estimates were made:

$X_t = 2 \times 10^{-13}$ radians/dyne cm.

$X_d = 2 \times 10^{-13}$ radians/dyne cm.

$X_g = 1 \times 10^{-13}$ radians/dyne cm.

$X_b = 1 \times 10^{-13}$ radians/dyne cm.



GEAR REQUIREMENTS PER UNIT

Gears:		Pinions:
1" - 6¾"	p.d. (internal)	2 - ¾" p.d.
2" - 2"	p.d (spur)	2 - ½" p.d
2 - 2"	p.d (")	2 - ½" p.d
2 - 1⅔"	p.d (")	1 - ⅓" p.d

All gears are A.S. Stub Tooth, Involute, diametral pitch 48 and pitch angle 20°.

All gears cut from bronze, S.A.E. 62.

All bearings tight tolerance bearings.

FIGURE 1.1.—High frequency gear train.

and the total compliance $X = 6 \times 10^{-13}$ radians/dyne cm., giving $f_g = 100$ cycles/second. Thus it would be expected that compliance in the gear trains would not contribute appreciably to instability of the servo system. The performance obtained in practice is discussed in section 1.4.

1.3.2 *The Design of the Platform Gimbals*

Resilience in the platform and gimbals can contribute to servo instability, and it is necessary to consider bending in the platform, the gimbals and the associated shafts and bearings. The best design aims at a reasonable compromise between rigidity and inertia.

The gimbals were machined from aluminum castings, with the long sides channeled and the ends left full for greater rigidity. The compliance of a gimbal about its axis of symmetry parallel to the long side is the sum of the compliance due to bending of the long sides, that due to bending of the ends, and that due to torsion in the ends; or

$$X = \frac{1}{2b^2}\left(\frac{a^3}{6EI_1} + \frac{a^2b}{E_nI_2} + \frac{b^3}{3EI_3}\right)$$

where $2a$ = length of long side
$2b$ = length of end
E = Young's modulus
E_n = Modulus of rigidity
I_1 = second moment of area of side for bending
I_2 = polar second moment of area of end
and I_3 = second moment of area of end for bending.

By the above formula, the compliance of the inner gimbal (C in Plate I) was calculated to be 1×10^{-13} radians/dyne cm., which is considerably less than that of the gear train. The outer gimbal E is adequately rigid to ensure accurate alignment of the bearings—its compliance does not enter directly into the stability of the servo systems.

When the assembly and wiring of the platform system had been completed, it was found that the range of motion of the platform was $+50°$ to $-60°$ in pitch, and $+60°$ to $-70°$ in roll. The ranges are considered adequate for transport aircraft under survey conditions.

The moments of inertia of the platform assembly were estimated at about 2×10^6 gm. cm^2. for the roll system, 1×10^6 gm. cm^2 for the pitch system and 6×10^5 for the azimuth system. The reflected moments of inertia of the rotors of the servomotors are 2×10^6 gm. cm^2.

1.3.3 *Gyroscope and Accelerometer Mounting*

The mounts fixing the gyroscopes to the platform must be rigid to avoid servo instability, but must also have a low thermal conductivity to reduce thermal distortion of the platform system and reduce warming-up time. The mounting rings of the platform gyroscopes and accelerometers are clamped down on bakelite insulating rings, $\frac{3}{16}''$ thick, by means of annular aluminum clamps. The bakelite rings are countersunk into the platform. The natural frequency of the mount is designed to be 10^4 cycles/second.

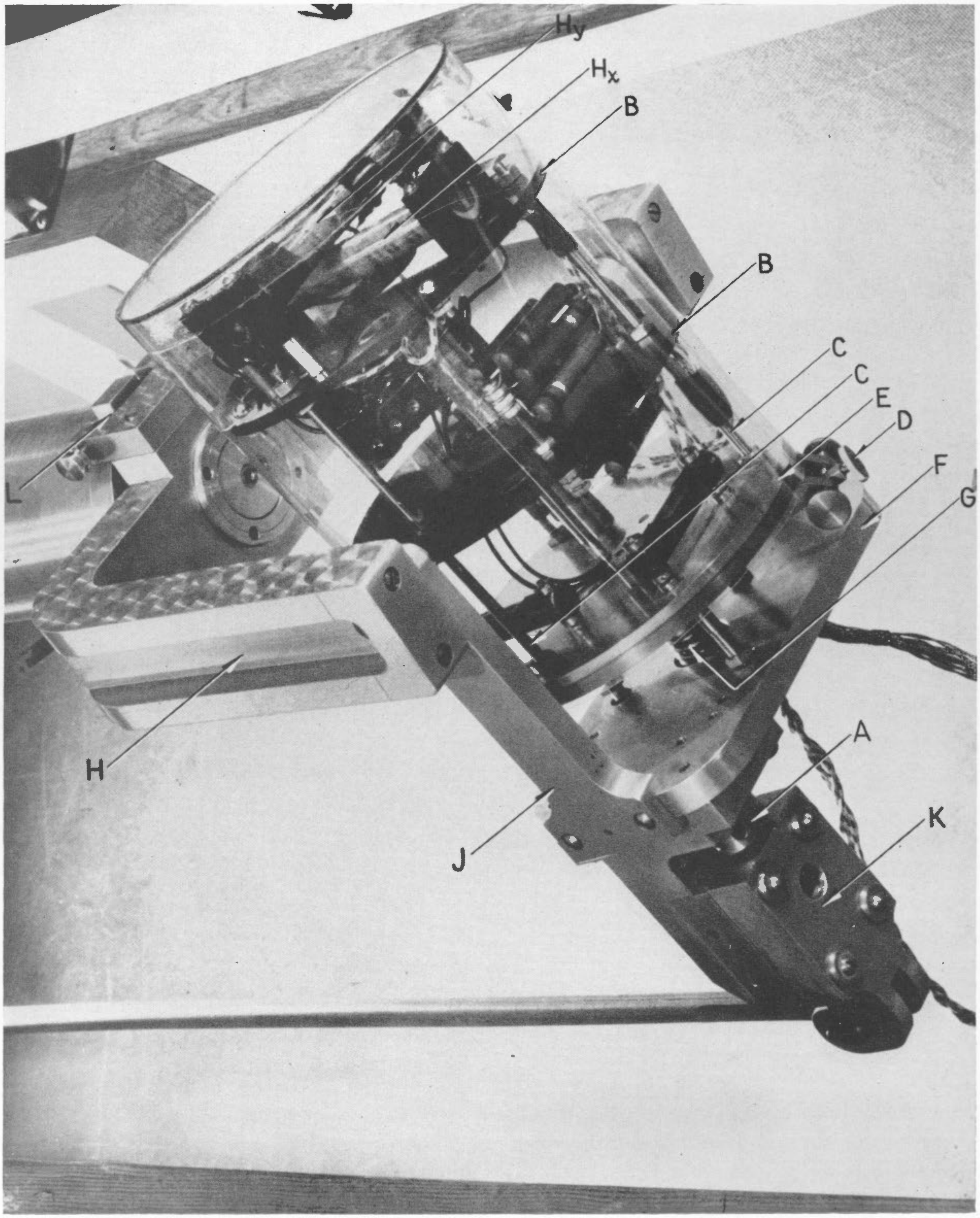


PLATE II—The magnetometer head.

1.3.4 *The Roll Transmission System*

The magnetometer yoke N (Plate I) is stabilized in roll by the pipe H connecting it rigidly to the inner gimbal C. The pipe is machined from a section of aluminum conduit, with inside diameter 3.07 inches, outside diameter 3.49 inches, and length 2.5 feet. Laboratory tests showed that at this distance the effect of magnetic components, such as ball bearings and servomotors, at the magnetometer head would be less than 10 gammas. The natural frequency of bending of the pipe with a 10-lb. load on the free end is nearly 60 cycles/second.

Cast aluminum plugs are welded into both ends of the pipe. The plug at the platform end carries an oilite collar which rotates in an oilite bearing in the outer gimbal E. The plug extends through the outer gimbal to the inner gimbal, to which it is clamped by a nut. The plug is 2.0 inches in diameter where it passes through the outer gimbal, and is strong enough to support a load of 100 lb. at a distance of 3 feet.

1.3.5 *The Pitch Transmission System*

As the aircraft pitches, the magnetometer platform is maintained parallel to the gyroscope platform by a mechanical linkage in the form of a parallelogram. The upper side of the parallelogram is 48 inches long and consists of the pipe H (Plate I), part of the inner gimbal C and the yoke N; the lower side is the $\frac{1}{2}$-inch-diameter aluminum link J. The ends of the parallelogram are 10 inches long and are formed by two platforms with their extensions projecting vertically downward (*see* K in Plate II).

In order that pitch angles with a range of $\pm 30°$ be transmitted with a maximum error of 1 minute, it is necessary that the horizontal sides of the parallelogram be equal to within .002 inches and the vertical sides be equal to .005 inches. The lengths of the link J (Plate I) and the vertical arm K (Plate II) can be adjusted by means of two turnbuckles. Each turnbuckle has threads of 12 to the inch and 13 to the inch operating differentially. A rotation of 60° changes the length by .001 inches.

The adjustment of the parallelogram is made on the ground by the following procedure. The gyroscope platform is rotated manually until the axis of the turntable is vertical within 0.2 minutes, as indicated by the level bubble on the turntable. The pitch level bubble in the magnetometer head is then brought to centre by means of the levelling screws under the head. One end of the platform assembly is raised by 2 feet, the gyroscope platform re-levelled and the transmission error read at the bubble at the magnetometer head. The error is read again with the other end of the platform assembly raised. The length of the horizontal link is adjusted to make the errors equal and of opposite sign. Then the vertical arm is adjusted to reduce the errors to less than 0.5 minutes, and the turnbuckles are firmly clamped.

It was calculated that, in operation, bending and compression in the parallelogram would produce errors of less than 0.1 minutes. No thermal distortion of the parallelogram could be observed as the gyroscopes heated or cooled.

The horizontal link is supported at each end by a $\frac{1}{4}$-inch bronze pin which turns in two R2 ball bearings set in the forked end of the vertical arm. Ball bearings are used to reduce backlash in the linkage. Their magnetic field is negligible at the magnetometer head.

1.3.6 *The Magnetometer Head*

The complete magnetometer head is shown in Plate II. The three orthogonal detecting elements and the thermostat heaters are mounted on the two bakelite plates, B. One of the two horizontal coils can be adjusted in azimuth relative to the other in slots in plate B. The axes of the detecting elements can be levelled by adjusting the nuts on the three threaded brass rods, C, which support the bakelite plates.

The non-magnetic base, E, of the magnetometer head contains a vertical axis with clamping screw D and two level bubbles similar to a theodolite base. The base is fixed to the magnetometer platform, F, by three threaded brass legs, which permit levelling the head assembly in pitch and roll independantly. A heavy brass spring, G, made of four turns of $\frac{1}{8}$-inch-diameter spring wire wound on a $\frac{3}{4}$-inch-diameter form, facilitates the levelling adjustment.

The platform F is made of 0.5-inch-thick aluminum and is supported from the magnetometer yoke H by substantial shaped aluminum arms, J. The two arms J carry at their upper ends 0.5 inch brass pins which turn in oilite bearings. One of the oilite bearings is a thrust bearing with a $\frac{1}{8}$-inch bakelite spacer between the arm and yoke.

The yoke was machined from an aluminum casting with a 2-by-1-inch section, except at the centre where it was thickened to three inches. The yoke has 1-inch channelled sides parallel to the roll axis. Tangent screws at L allow the yoke to be adjusted about the roll axis before it is clamped to the plug by a nut of $1\frac{1}{2}$-inch internal diameter.

The magnetometer platform assembly was designed to allow rotation of $\pm 70°$ in pitch. Great care was taken to avoid the use of any magnetic material in its construction.

1.3.7 *The Platform Mount*

This is seen in Plate I. The frame consists of wooden two by threes, with 1-inch runners, $1\frac{1}{2}$ inches deep and 42 inches long (P in Plate I), which fit into the channels of the outer gimbal, E. The outer gimbal is securely bolted by four heavy brass bolts to the frame, which is shockmounted to a sturdy wooden box, using four Lord multiplane shockmounts, Q. The box is tied to the floor of the aircraft using aluminum angle brackets and bolts, and is supplied with a cover fitted in three parts. This cover is not shown in Plate I.

The outside dimensions of the box, with cover on, are 81 inches long, 27 inches wide and $32\frac{1}{2}$ inches deep. The construction used is strong enough to avoid accidental damage to the platform under field conditions.

1.3.8. *The Shockmounting of the Units*

The centre of gravity of the mechanical system and its wooden frame is 28 inches from the outside edge of the frame and the total weight of the platform and frame is 127 pounds. The four dural multiplane vibration isolators, which shockmount the assembly, are placed symmetrically about the centre of gravity and separated along a line parallel to the roll axis by four feet. These shockmounts, designed so that their radial and axial spring rates are equal, can be seen at Q in Plate I. Shockmounts rated at 45 pounds load are used. From the data supplied by the manufacturer, it was estimated that these should provide good vibration isolation at frequencies above about 12 c.p.s. Duraluminum assembling washers are used to form a mechanically interlocked system and to prevent excessive frame movement.

The estimated moment of inertia about a line through the centre of gravity parallel to the axis of pitch is 3.5×10^4 lb. in^2. From the deflection characteristics of the mounts it was calculated that the natural frequency of the system is 13 c.p.s. The corresponding force constant is 5.5×10^5 lb. in./radian. This natural frequency is somewhat low, but the low force constant did not produce instabilities in the platform servo systems at the natural frequencies achieved in practice. Similar considerations hold for vibrations about the roll axis.

It is convenient to note here that a number of 45-lb. vertical snubbing shockmounts are used to support the two chassis racks containing the electronic control equipment. Eight mounts are used for each rack and proved so successful in operation that no failures attributed to vibration have occurred in flight operation to date.

1.3.9 *The Azimuth Slip Ring System*

The directional gyro, K, of Plate I, and its turntable have complete freedom of rotation about a vertical axis, and therefore it is necessary to transmit signals and power to and from the units through slip rings and brushes. The slip rings are concentric silver rings cemented into a grooved plastic bed, which fits into the top plate of the azimuth gear train in the position shown in Figure 1.1. The brushes rotate with the gyro turntable, L. This design allowed uniformity of manufacture of the three platform gear trains, and avoided large increases in size, and hence in inertia, about the pitch axis.

The twelve rings were cut from a single silver plate, $\frac{1}{8}$ inch thick. They are $\frac{1}{10}$ inch wide and the spacing between successive rings is $\frac{1}{20}$ inch. The twelve screws making connection to the rings are brought out through a slot in the perspex plate. The brushes are of a commercial silver-graphite construction containing 85 per cent silver. Each brush is fitted with a flexible and a spiral spring. The brushes are divided into two groups of six, and mounted in two plastic blocks seated in the turntable L along a diameter, one on each side of the directional gyro mount, M. One of these blocks can be seen at R in Plate I. The brushes are held vertically in sleeves in the plastic blocks, and the spring compression is such that they operate at a pressure of about six lb./sq. inch. The frictional torque is then less than 0.2 lb. inch, or about one six-hundredth of the azimuth servomotor maximum output torque.

Eight of the twelve brushes have a cross-section 4mm $\times$ 3mm and four have a cross-section 10mm $\times$ 3mm. Two of the larger-section brushes are used to carry the directional gyroscope heater current. A switch at the gyroscope allows the selection of either the 5 or the 10-ohm heating coils. The lower resistance corresponds to a current of 5 amperes, or a current density of approximately 100 amp./sq. inch, and a potential drop across each brush of 0.2 volts. No trouble is caused by the relatively high figure of 1 watt brush dissipation while the gyroscope is warming up with the 5-ohm coil being used. After the gyroscope has reached operating temperature the brush dissipation is no longer continuous, and in any case is much reduced with the use of the 10-ohm heater.

The other two large brushes carry the much smaller single phase current to the gyroscope motor, and the eight smaller section brushes are distributed among the remaining circuits. In no case does the current through any of the smaller-section brushes exceed 100 m.a., which corresponds to a maximum contact drop of 3mV with these brushes and silver slip rings.

1.4 THEORY OF THE PLATFORM SERVOMECHANISMS

An outline of the theory of the pitch and roll servo systems is given below. The azimuth system is simpler theoretically but its performance is much the same.

In the design of the platform servomechanisms, two considerations are obvious. In order that the gyroscopes will not be disturbed, the servomotors should respond quickly to the angular motions of the aircraft, and should produce a large torque for small gyro errors, so that torques due to mechanical unbalance of the platform and flexure of the wiring will have a negligible effect. Preliminary measurements showed that, in rough air, angular velocities of the aircraft of 20°/sec. are not unusual. The ratio chosen for the platform gear trains (720 to 1) allows the servomotors to cancel angular velocities of the aircraft up to 44°/sec. The damping of the servo systems should be mainly of the error-rate type rather than viscous to avoid velocity-lag errors. Integral control was rejected because of the transient errors which it can introduce.

To obtain a value of the torque gain G on which the preliminary design can be based it is specified that the velocity-lag error at the platform should be less than 1 minute of arc for an angular velocity of the aircraft of 20°/sec. Then

$$G > \frac{\text{Angular velocity} \times \text{viscous damping}}{\text{velocity-lag error}}.$$

For the Kollsman Type R111-2A two-phase servomotors used on all three platform axes, we obtain $G > 2 \times 10^{11}$ dyne cm/rad., measured at the platform, corresponding to a torque of 4 ft. lb. for a displacement of the platform of 1 minute of arc.

The equations of motion of one of the servo systems are now described using the notation of Table 1.1. The gyroscope pick-off gives an electrical signal proportional to the error of the system, the angle ϕ. This signal is applied through an amplifier to a servomotor, producing a torque G(s) in a sense tending to reduce ϕ. The general case when the gyroscope output axis is at an angle θ to the true vertical is examined, and the equations of motion are obtained when the reference line in the aircraft is at an angle α to the true vertical. The relationships between the reference axis and the axes of the gyroscope are illustrated in Figure 1.2.

Consider torque about the axis Oz; then

$$T_1 = Hr - H\dot{\theta} - J_1(\ddot{\psi} - \ddot{\phi}) + K_1\dot{\phi} \qquad \text{Eqn. (1)}$$

Consider torque about the axis Oy; then

$$-G\phi = -N(J_2\ddot{\theta}_1 + K_2\dot{\theta}_1) - \frac{1}{X}\left[(\theta - \alpha) + \frac{\theta_1}{N}\right] + J_2\ddot{\alpha} \qquad \text{Eqn. (2)}$$

and $$-\frac{1}{X}\left[(\theta - \alpha) + \frac{\theta_1}{N}\right] = -H(\dot{\psi} - \dot{\phi}) + J_3\ddot{\theta} + K_3(\dot{\theta} - \dot{\alpha}) \qquad \text{Eqn. (3)}$$

TABLE 1.1—LIST OF SYMBOLS

Symbol	Meaning
J_1	Moment of inertia of gyroscope gimbal about output axis of gyroscope
J_2	Moment of inertia of servomotor driving platform
J_3	Moment of inertia about axis of rotation under discussion
K_1	Viscous damping constant between gyroscope gimbal and case
K_2	Viscous damping constant of servomotor
K_3	Viscous damping in gear train
N	Step down gear ratio between servomotor and platform
H	Angular momentum of gyroscope rotor
X	Angular compliance of gear train (angular deflection at output per unit torque)
G(s)	Frequency dependent torque gain of servo loop
r	Wander rate of gyroscope, including component of earth's rate
T_1	Torque applied about output axis to gyroscope gimbal by torque generator.
θ	Angle between true vertical and case of gyroscope
ϕ	Angle between Ox axis and axis of gyroscope rotor
ψ	Angle between true North and Ox axis
α	Angle of pitch or roll of aircraft frame
θ_1	Angle through which servomotor turns with respect to the aircraft frame

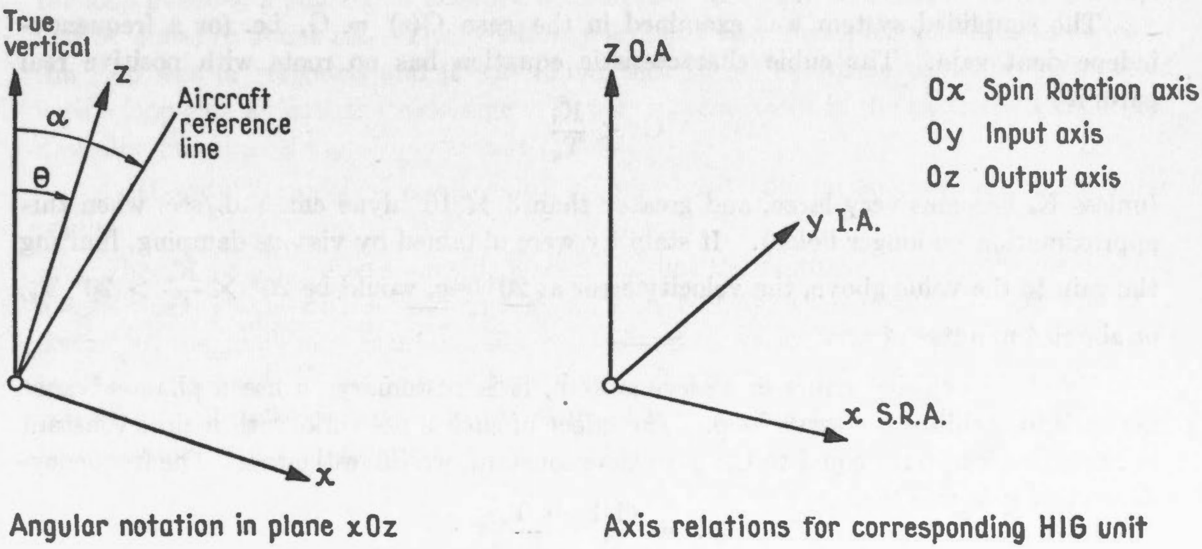


FIGURE 1.2.—Notation used in discussion of platform servomechanisms.

In equation (2) the term $J_2\ddot{\alpha}$ can be neglected since it represents the acceleration of the servomotor rotor through space, and is much smaller than N J_2 $_1$.

Define $(\theta + \alpha) + \frac{\theta_1}{N} = \epsilon$ Equations (1) to (3) can be written in Laplacian notation

$$Hs\theta - (J_1s^2 + K_1s)\,\phi = -\,T_1 + Hr - J_1s^2\,\psi$$

$$N^2(J_2s^2 + K_2s)\,\theta + G(s)\,\phi - \left[N^2(J_2s^2 + K_2s) + \frac{1}{X}\right]\epsilon = N^2(J_2s^2 + K_2s)\,\alpha$$

$$(J_3s^2 + K_3s)\,\theta + Hs\phi + \frac{1}{X}\,\epsilon = Hs\psi + K_3s\alpha$$

The characteristic equation is then

$$\begin{vmatrix} Hs & -(J_1s^2 + K_1s) & 0 \\ N^2(J_2s^2 + K_2s) & G(s) & -\left[N^2(J_2s^2 + K_2s) + \frac{1}{X}\right] \\ J_3s^2 + K_3s & Hs & \frac{1}{X} \end{vmatrix} = 0 \qquad \text{Eqn. (4)}$$

The conditions for stability were investigated in two ways: in each case a preliminary study was made of a mechanically perfect gear box with $X = 0$, and hence $\epsilon = 0$. Then the characteristic equation reduces to

$$\begin{vmatrix} 1 & -(1 + T_g s) \\ (J_4s^2 + K_4s) & Hs + G(s) \end{vmatrix} = 0 \qquad \text{Eqn. (5)}$$

where $N^2J_2 + J_3 = J_4$, and $N^2K_2 + K_3 = K_4$ by definition, since $K_1 = H$ and $\frac{J_1}{K_1} = T_g$, the gyro time constant.

First Method: The system is known to be stable and non-oscillatory if there exist no roots of the characteristic equation with positive real parts.

The simplified system was examined in the case $G(s) = G$, i.e. for a frequency-independent gain. The cubic characteristic equation has no roots with positive real parts if

$$G < \frac{K_4}{T_g}$$

(unless K_4 becomes very large, and greater than 3×10^9 dyne cm./rad./sec. when this approximation no longer holds). If stability were obtained by viscous damping, limiting the gain to the value above, the velocity error at 20°/sec. would be $20° \times \frac{K_4}{G} > 20°\ T_g$, or about 4 minutes of arc.

To avoid velocity errors in a servo system, it is customary to use a phase-advance network to stabilize the servo loop. The effect of such a network, with a time constant in the phase lead term equal to the gyro time constant, was investigated. The frequency-dependent gain was then

$$G(s) = \frac{G(1 + T_g s)}{1 + \frac{T_g s}{M}}$$

where M is >1. The characteristic equation was a quartic and the condition for stability for reasonable values of K_4 became $G < \frac{MK_4}{T_g}$.

The determinantal method becomes very cumbersome if the non-rigid system with springiness is considered. If the effect of a frequency-dependent gain of the form

$$G(s) = G\,\frac{1 + T_1s}{1 + T_2s}$$

is investigated with a non-rigid system, the characteristic equation becomes sixth order.

However, an approximate trial determination with an error-rate network introducing a phase lead $T_1 = T_g$ showed that for stability in the compliant case

$$G < 8 \times 10^{11} \frac{1 + 2 \times 10^{-9} K_4 + 3 \times 10^{-21} \frac{K_4}{X}}{1 + 2 \times 10^{-9} K_4}$$

where G is in dyne cm./radian, and K_4 and X in c.g.s. units.

For a heavily damped gear box and a high-frequency gear train this reduces to the simpler condition $G < \frac{1}{X}$. Thus, for $G = 2 \times 10^{11}$ dyne cm./ rad, $X < 5 \times 10^{-12}$ rad./ dyne cm. This result was deduced earlier in the discussion of the design of the high-frequency gear trains. The degree of stability of the system is not determined by this algebraic method.

Second Method: The stability of the servo system was investigated by the Philbrick analog computer in the Division of Electrical Engineering in the National Research Council, Ottawa.

Because of the limited number of computer sub-units available, it was necessary to neglect the resilience of the gear trains. With this approximation the computer showed that the servo system should be stable with a torque gain of 2×10^{11} dyne cm./radian, if the loop included a phase lead network with a phase lead time constant of 10 milliseconds, and M equal to about six. The possibility of using two error-rate networks in series in the loop was investigated and it was found that stable operation could be maintained with a loop gain at least twice as large. Equal time constants in the two networks seemed desirable but the relationship was not critical.

A laboratory model of one servo loop was built and tested, and confirmed these results.

When the platform was built, it was found that the platform servomechanisms could not be made stable with a gain as high as 2×10^{11} dyne cm./rad. Consequently the design of the amplifiers was actually carried out empirically, trying different circuits and time constants in the phase-advance and filter circuits. The characteristics of the amplifier finally adopted as the most reliable over a reasonable range of adjustment can be expressed approximately by

$$G(s) = \frac{1 + .040\ s}{1 + .004\ s} \times 3.0 \times 10^{10} \text{ dyne cm./rad.}$$

Inserting this value of G(s) in equation (5), and neglecting some high-order terms and gear train damping, a characteristic equation of the third order is obtained:

$$s^3 + 1.7 \times 10^2 s^2 + 4.7 \times 10^4 s + 1.0 \times 10^6 = 0.$$

By well-known methods of solution (8), it can be shown that the transient error is then of the form $\theta = Ae^{-25t} + Be^{-74t} \cos 2\pi\ (32t)$. Thus transient errors decay to 10 per cent of their initial value in less than 0.1 seconds.

Although the loop gain achieved in practice is 7 times less than that aimed at in the design of the gear trains, the frequency of the oscillatory part of the preceding transient solution (32 cycles/sec.) approaches the natural frequency roughly calculated in section 1.3.1 (35 cycles/sec.). This may account for the lack of success in obtaining stability at the higher gain. The velocity-lag error with the lower gain is of course 7 minutes of arc for aircraft velocities of 20°/second. It should be noted that the velocity-lag error of the gyroscope is equal to that of the platform since at operating temperature the gimbal transfer function of the gyroscope $H/K_1 = 1$.

1.5 THEORY OF THE VERTICAL STABILIZATION SYSTEM

Airborne vertical reference systems including various combinations of gyroscopes and accelerometers have been systematically compared by Mack (5) on the basis of their theoretical performances using gyroscopes now available. Mack's discussion of the system used in the three-component airborne magnetometer is reproduced here, with slightly modified notation.

The following notation will be used throughout this section:

In the horizontal plane

V = ground speed of the aircraft
D = angle between the ground speed vector and the roll axis of the aircraft
ψ = true heading of the roll axis of the platform
λ = west longitude
ϕ = north latitude
ω = angular velocity of the earth
g = acceleration of gravity
a = horizontal component of the acceleration of the aircraft with respect to the earth
a_v = vertical component of the acceleration of the aircraft with respect to the earth.

Two vertical planes are considered, one containing the roll axis and the other normal to it. The vertical stabilization system establishes reference directions, given by the directions of the spin axes of two HIG gyroscopes, from which angles can be measured. Angles measured in the plane containing the roll axis will be indicated by the subscript p for pitch, and those measured in the other vertical plane will be indicated by the subscript r for roll.

The true vertical is defined as the direction of gravity. This is not a fixed direction in space because the earth is rotating. The coordinate system chosen by the planes defined above is a non-inertial system because the aircraft to which it is attached may be subject to accelerations a, which are functions of time. According to D'Alembert's principle, we may treat it as an inertial system provided a fictitious force $-ma$ is supplied to each mass, m. The equilibrium position of a pendulum in this system is called the apparent vertical, and is in the direction of the vector sum of $-a$ and g. In normal flight a is much less than g.

An accelerometer is a device which measures the component of acceleration along its sensitive axis. Two Minneapolis-Honeywell HAU accelerometers are mounted on the stabilized platform. One accelerometer has its sensitive axis parallel to the roll axis of the platform, and the other is perpendicular to it. The outputs of the accelerometers

a_p and a_r thus contain the components of the vector acceleration a about the pitch and roll axis respectively, together with the components of gravity along their axes produced by platform tilt.

Since the acceleration vector can be resolved into two components, one $\frac{dV}{dt}$ parallel to the velocity vector, and the other $V\left[\frac{d\psi}{dt} + \left(\frac{d\lambda}{dt} - 2\omega\right)\sin\phi\right]$ normal to it, resolution along the roll and pitch axes of the platform gives

$$a_p = (g + a_v)\,\theta_p + \frac{d}{dt}(V\cos D) - V\sin D\left[\frac{d\psi}{dt} + \left(\frac{d\lambda}{dt} - 2\omega\right)\sin\phi\right] \qquad \text{Eqn. (6)}$$

$$a_r = (g + a_v)\,\theta_r + \frac{d}{dt}(V\sin D) + V\cos D\left[\frac{d\psi}{dt} + \left(\frac{d\lambda}{dt} - 2\omega\right)\sin\phi\right] \qquad \text{Eqn. (7)}$$

where θ_p, θ_r are the angles between the true horizontal plane and the roll and pitch axes of the platform respectively, i.e. are the components of platform tilt. Neglecting wind, equations (6) and (7) can be written

$$a_p = (g + a_v)\,\theta_p + \dot{V} \qquad \text{Eqn. (8)}$$

$$a_r = (g + a_v)\,\theta_r + V[\dot{\psi} + (\dot{\lambda} - 2\omega)\sin\phi] \qquad \text{Eqn. (9)}$$

We note that $-2\omega V\sin\phi$ is the horizontal component of the well-known Coriolis acceleration and $\dot{\lambda}\sin\phi$ is the rate of converging of meridians at latitude ϕ.

Let the natural wander-rates of the two gyroscopes used be r_p, r_r measured about the appropriate reference axes. The gyroscopes precess away from the vertical because the vertical changes direction in space as the earth rotates and as the aircraft moves over the earth's surface. The components of platform tilt, θ_p and θ_r also change when the aircraft heading changes. It can be shown that because an aircraft, even when flying straight, may have fluctuations in azimuth of the order of 2°, θ_p and θ_r must be less than 0.5° to keep any error in the system due to apparent gyroscope fluctuations less than one minute of arc. This difficulty is removed when the gyroscopes are mounted on the stabilized platform. The fundamental problem of vertical stabilization is to find a system satisfying

$$\theta_p = \theta_r = 0 \qquad \text{Eqn. (10)}$$

$$\dot{\theta}_p = \dot{\theta}_r = 0 \qquad \text{Eqn. (11)}$$

Equation (10) shows that some form of closed loop control must be used, and equation (11) can only be satisfied if corrections are applied at appropriate points in the loop to compensate for the effects described above. The closed loop control must also compensate for the natural wander rate of the gyroscope.

The linear erection system with integral control used for the airborne magnetometer is now described. In his discussion, Mack (5) has shown that this system makes fewer demands upon gyroscope performance than do the other schemes he described. The system is self-checking in that a change in wander-rate becomes apparent from a change in the output of the integrators. The platform can be erected at any time during flight, and oscillations of the system can be damped without introducing errors into the determination of the vertical.

Figure 1.3 shows the projections of the directions considered above as they appear on either of the planes of reference. A generalized symbol is used for both the roll and pitch cases, which are theoretically equivalent. Since in normal flight, horizontal accelerations are much less than g, $\delta = -a/g$.

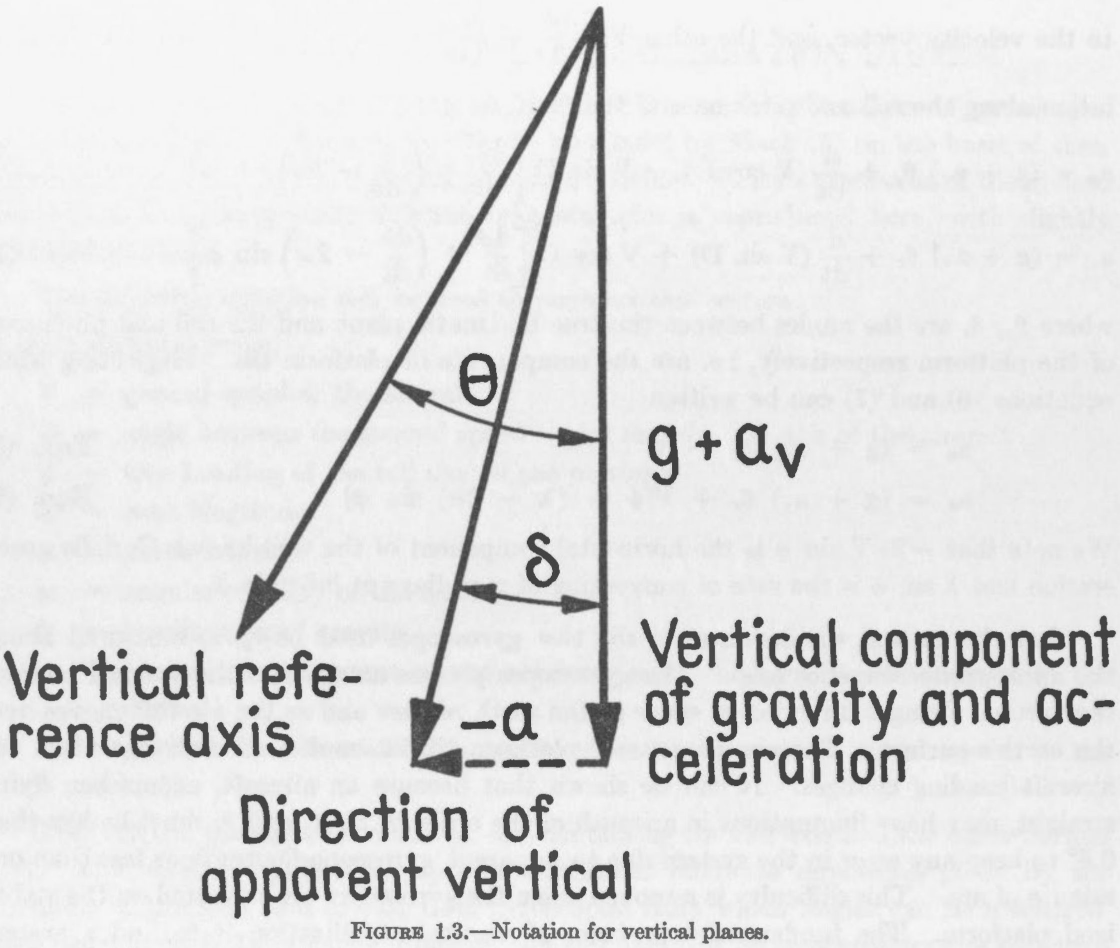


FIGURE 1.3.—Notation for vertical planes.

The control system produces a torque $F(t) \times (\theta - \delta)$ which erects the gyroscope according to the equation

$$\frac{d\theta}{dt} = r - \omega_c F(t) \times (\theta - \delta) \qquad \text{Eqn. (12)}$$

where r is the gyroscope wander rate, and ω_c is a reciprocal time constant.

Taking the Laplace transform of equation (12), we have

$$s\theta(s) = r - sY(s)\,[\theta(s) - \delta(s)] \qquad \text{Eqn. (13)}$$

where $\quad s\,Y(s) = \omega_c\, L\,\{\,F(t)\,\}$

Assuming Y(s) is the transform of a linear differential operator,

then $$\theta = \frac{Y\delta}{1 + Y} + \frac{\frac{r}{s}}{1 + Y} \qquad \text{Eqn. (14)}$$

In equation (14), r represents the uncorrected and random wander rate of the gyroscope, the rate associated with the earth's rotation being compensated for.

The requirement that the system behaves as a sharp-cut-off filter to periodic accelerations δ, places a condition on the form of Y(s). A reasonably sharp cut-off is obtained if

$$\lim_{s \to \infty} \frac{Y(s)}{1 + Y(s)} \approx \left(\frac{\omega_n}{s}\right)^2 \to 0$$

where ω_n is a reciprocal time constant. The requirement for zero steady state error due to gyro wander is

$$\lim_{s \to 0} \frac{\frac{r}{s}}{1 + Y(s)} \approx k_1\, s \to 0, \text{ i.e. } \lim_{s \to 0} s\, Y(s) \approx \frac{k_2}{s} \to \infty$$

From the consideration of these limits, it is deduced that a control Y(s) of the form

$$Y(s) = \left(\frac{\omega_n}{s}\right)^2 \frac{s^n + b_{n-1}\, s^{n-1} + \ldots + b_0}{s^n + a_{n-1}\, s^{n-1} + \ldots + a_0} \qquad \text{Eqn. (15)}$$

is required.

A mechanical filter has been described by Serson (6) and Mack (7) with a transfer function

$$Y(s) = \left(\frac{\omega_n}{s}\right)^2 \frac{s^2 + 2g_1\, \omega_1\, s + \omega_1^2}{s^2 + 2g_2\, \omega_2\, s + \omega_2^2} \qquad \text{Eqn. (16)}$$

In the present arrangement, a simpler function is used of the form

$$Y(s) = \left(\frac{\omega_n}{s}\right)^2 \frac{s + a\, \omega_n}{s + b\, \omega_n} \qquad \text{Eqn. (17)}$$

An electrical circuit with this transfer function consists of two integrators in series with a phase-lead network of the type used in error-rate damping. While the mechanical filter described by equation (16) has a slightly better transient response than the electrical filter described by equation (17), the flexibility of the electrical system permits a more accurate realization of the transfer function and in practice better transient response is achieved electrically. Figure 1.4 is a schematic diagram of the gyroscope control system with the transfer function of equation (17) obtained by using an electrical filter.

In the following development the effects of wind and the velocity of the aircraft with respect to the earth are neglected, and the platform is assumed to be nearly horizontal.

Equation (14) now becomes

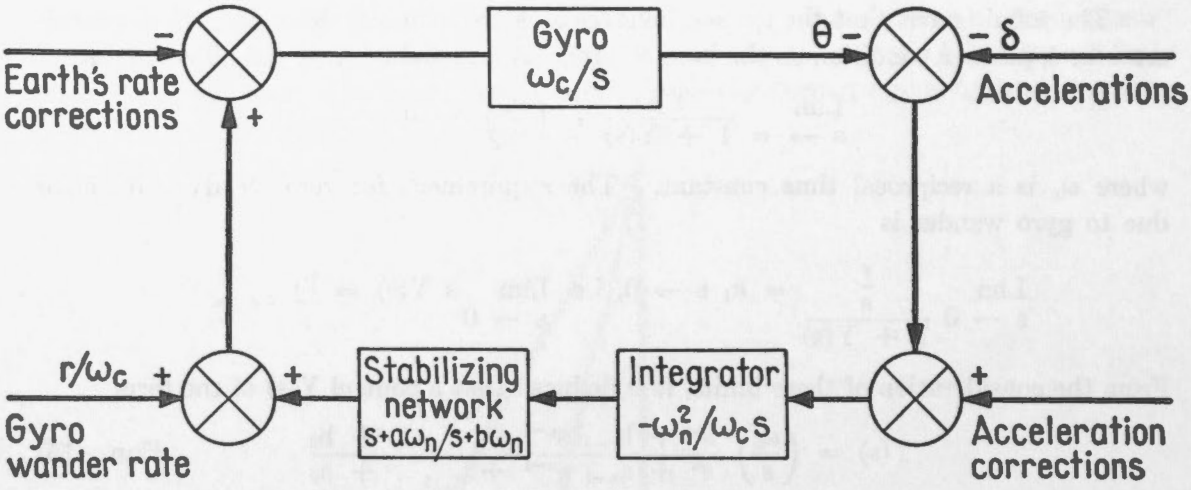
$$\theta = \frac{\omega_n^2\, (s + a\, \omega_n)\, \delta + s^2\, (s + b\, \omega_n)\, \frac{r}{s}}{s^3 + b\, \omega_n\, s^2 + \omega_n^2\, s + a\, \omega_n^3} \qquad \text{Eqn. (18)}$$

The characteristic equation is a cubic, and the relation between parameters for the optimum transient response is well known (8). The optimum values of a and b are $a = \frac{1}{4}$, $b = \frac{3}{2}$ and substituting these, equation (18) becomes

$$\theta = \frac{\omega_n^2\, (s + \frac{1}{4}\, \omega_n)\, \delta + (s + \frac{3}{2}\, \omega_n)\, rs}{(s + \frac{1}{2}\, \omega_n)\, (s^2 + s\omega_n + \frac{1}{2}\, \omega_n^2)}$$

Solving for a unit step in wander rate, $r = \frac{1}{s}$, we obtain

$$\theta = \frac{s + \frac{3}{2}\, \omega_n}{(s + \frac{1}{2}\, \omega_n)\, (s^2 + s\omega_n + \frac{1}{2}\, \omega_n^2)}$$



	Earth's Rate Corrections	Acceleration Corrections
Pitch plane	$\omega \cos\phi \sin\psi$	dV/dt
Roll plane	$\omega \cos\phi \cos\psi$	$V[d\psi/dt + (d\lambda/dt - 2\omega)\sin\phi]$

FIGURE 1.4.—Schematic of gyro erection system.

The inverse Laplace transform of this yields the following transient response

$$h_c(t) = 4e^{-\frac{1}{2}\omega_n t} - e^{-\frac{1}{2}\omega_n t}\left[4\cos\tfrac{1}{2}\omega_n t - 2\sin\tfrac{1}{2}\omega_n t\right].$$

The response to a unit impulse in r is defined as

$$h_b(t) = L^{-1}\left[\frac{\frac{1}{s}}{1+Y}\right] = \frac{d}{dt}\left\{L^{-1}\left[\frac{\frac{1}{s^2}}{1+Y}\right]\right\} = h_c(t)$$

and can thus be found by differentiation. The response to a unit impulse in δ is defined as $h_a(t) = -\dot{h}_b(t)$, since

$$h_a(t) = L^{-1}\left[\frac{Y}{1+Y}\right] = \frac{d}{dt}\left\{L^{-1}\left[\frac{Y}{s(1+Y)}\right]\right\}, \text{ and}$$

$$h_b(t) = L^{-1}\left[\frac{\frac{1}{s}}{1+Y}\right] = L^{-1}\left[\frac{1}{s} - \frac{Y}{s(1+Y)}\right]. \text{ Therefore}$$

$$h_a(t) = \frac{d}{dt}\left[L^{-1}\left(\frac{1}{s}\right) - h_b(t)\right] = -\dot{h}_b(t).$$

In Figure 1.5, $h_a(t)$, $h_b(t)$ and $h_c(t)$ are shown plotted as functions of time. Measurements in transport aircraft show that under good flying conditions, accelerations of the aircraft with periods of 1 or 2 minutes can be expected with amplitudes corresponding to a deflection of the vertical of 1 or 2 degrees. If the filtering action of the system is to attenuate these deflections to 1 minute of arc, the period of the system would have to be of the order of 15 minutes, and transients in the system would require a very long time to decay. As a compromise between good filtering and rapid decay of the transients,

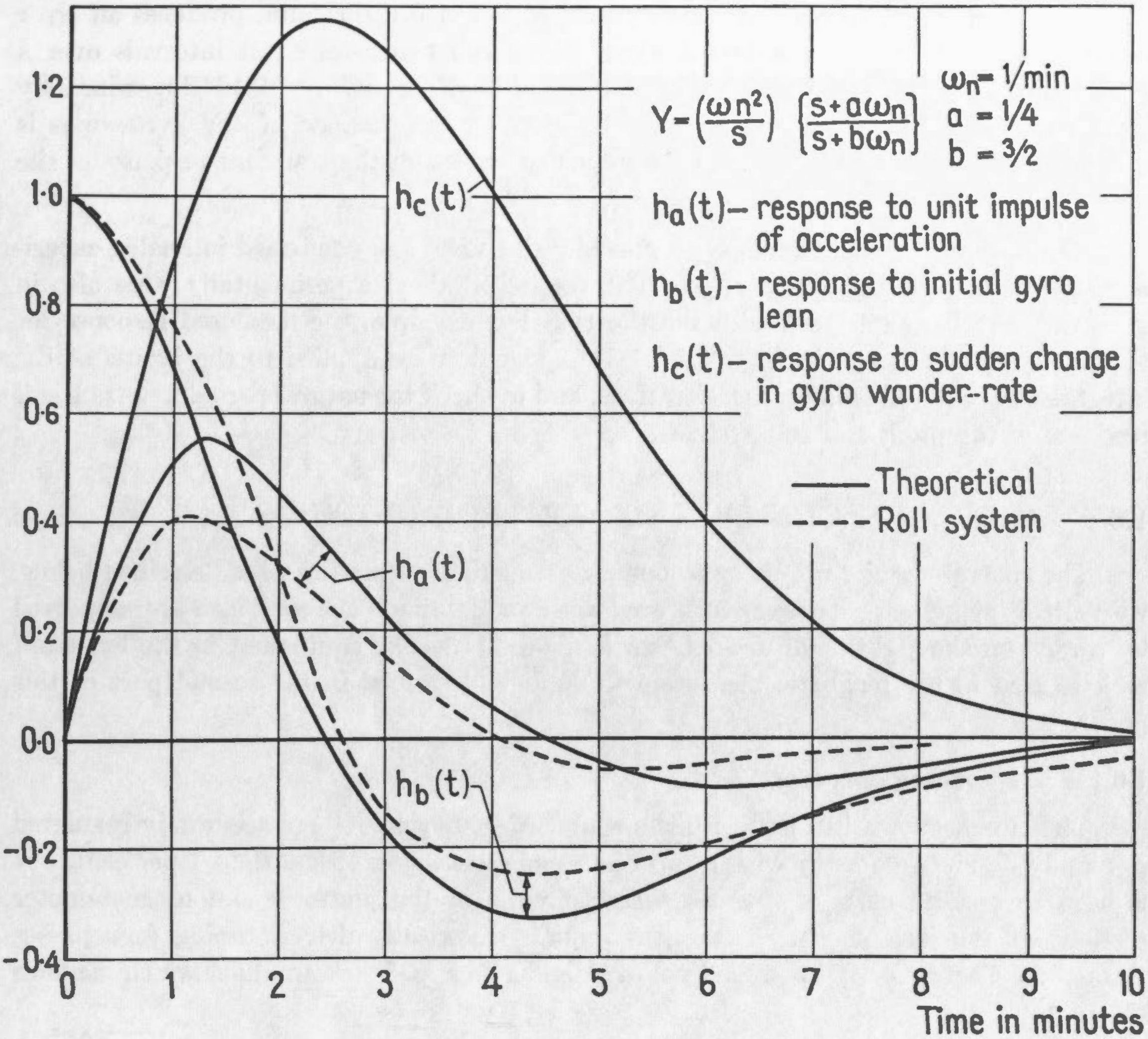


FIGURE 1.5.—Transient response of gyro erection system.

a period of 2π minutes was chosen for the filter, making $\omega_n = 1.0$ per minute. All three types of transients then fall to at least a tenth of their maximum value within 8 minutes.

The curves may be interpreted by considering the following fictitious, though typical, information: (a) suppose that the system is given an acceleration of 1° lasting for 1 minute. The curve $h_a(t)$ shows that a peak error of 0.55° or 33 minutes will build up. Nine minutes after the impulse was applied the error is reduced to 1 minute of arc. (b) suppose the platform has an initial lean of 0.5°. The curve $h_b(t)$ shows that 9 minutes after, the lean is reduced to 1 minute of arc. (c) suppose the wander rate r of either of the two platform gyroscopes suddenly changes by 10°/hr. The curve $h_c(t)$ shows that an error of 13 minutes of arc is built up and after 9 minutes this error is reduced to less than a minute of arc.

If the wander rate of one of the two platform gyroscopes has a constant rate of change, an error

$$\epsilon = L^{-1}\left[\frac{bsr}{a\omega_n^2}\right] = \frac{b\dot{r}}{a\omega_n^2}$$

is produced in the platform. A wander acceleration of 0.1°/hr./min. produces an error of 0.6 minute of arc. A number of gyros have been bench-tested at intervals over a period of four years, and wander accelerations of 0.03°/hr./min. to 0.12°/hr./min. only were obtained initially. The later deterioration in performance of the gyroscopes is discussed fully in section 3.6, where the influence of this on the transient response of the platform is outlined.

The optimum transient response considered above was confirmed in analog experiments with the Philbrick computer. The results obtained experimentally were also in good quantitative agreement with the theory. For example, the measured response for the roll system is shown in Figure 1.5. D.C. signals were applied to the inputs of the integrators to simulate aircraft accelerations, and to check the natural period and transient response of the pitch and roll systems.

1.6 DESCRIPTION OF CONTROL CIRCUITS

The control circuits necessary to operate the stabilized platform are described below, with circuit diagrams. These circuits are built into aluminum chassis which are supported by a rack on the right-hand desk shown in Plate III. The equipment in the left-hand rack is used in the magnetic measurements and is described in the second part of this paper.

1.6.1 *The Frequency Standard*

The circuit shown in Figure 1.6 is a source of 400-cycle voltage accurately regulated in amplitude and frequency with a total harmonic distortion of less than 1 per cent. It is used to operate most of the computing circuits in the platform and magnetometer sections of the instrument. The output of an electrically driven tuning fork passes through an electronically controlled voltage divider to a feedback amplifier which includes

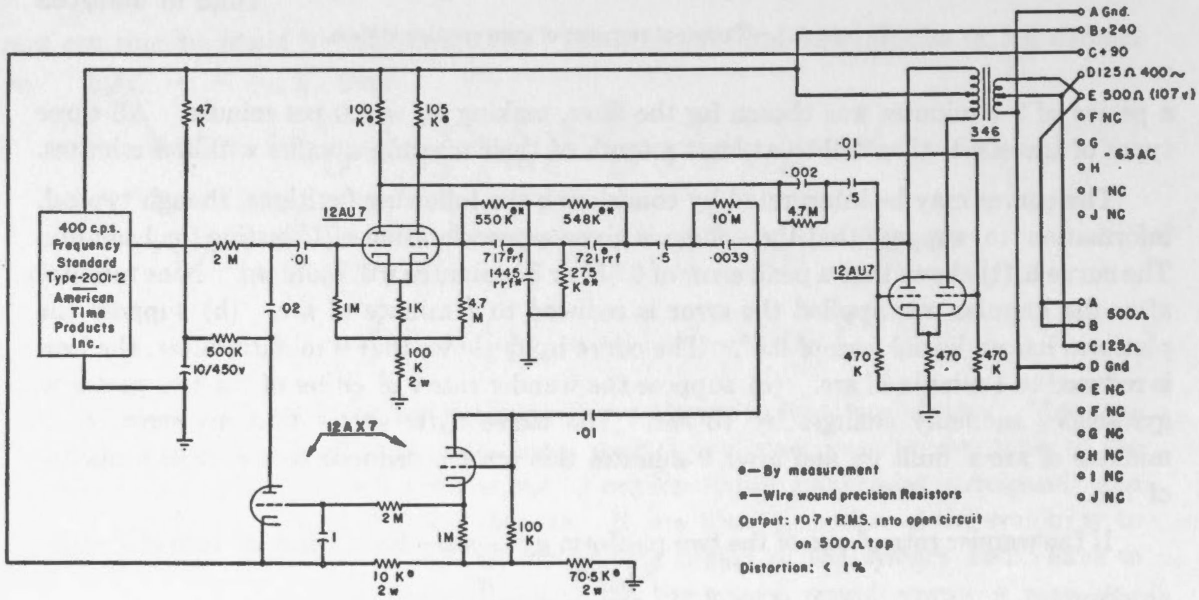


FIGURE 1.6.—Frequency standard.

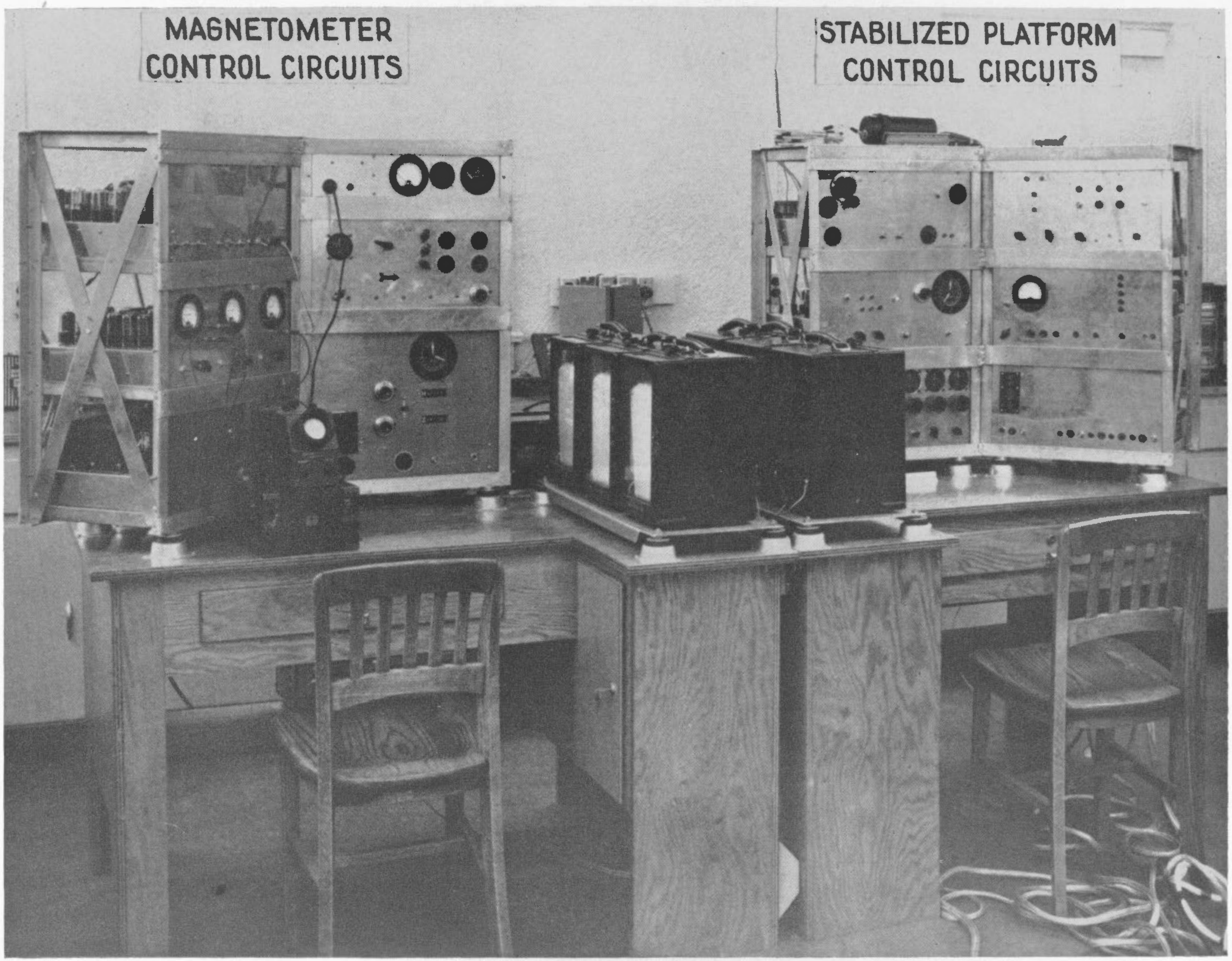


PLATE III—The control console.

a twin-T circuit to reduce harmonics. The output voltage of the amplifier is rectified and compared with a regulated D.C. reference voltage, and the difference controls the voltage divider.

When the magnetometer was first built, a 440-cycle tuning fork was used to avoid low-frequency beats with the 400-cycle aircraft inverters. Flight experience showed, however, that most aircraft inverters tend to operate nearer to 440 cycles than 400 cycles, and so the tuning fork was changed to a 400-cycle unit.

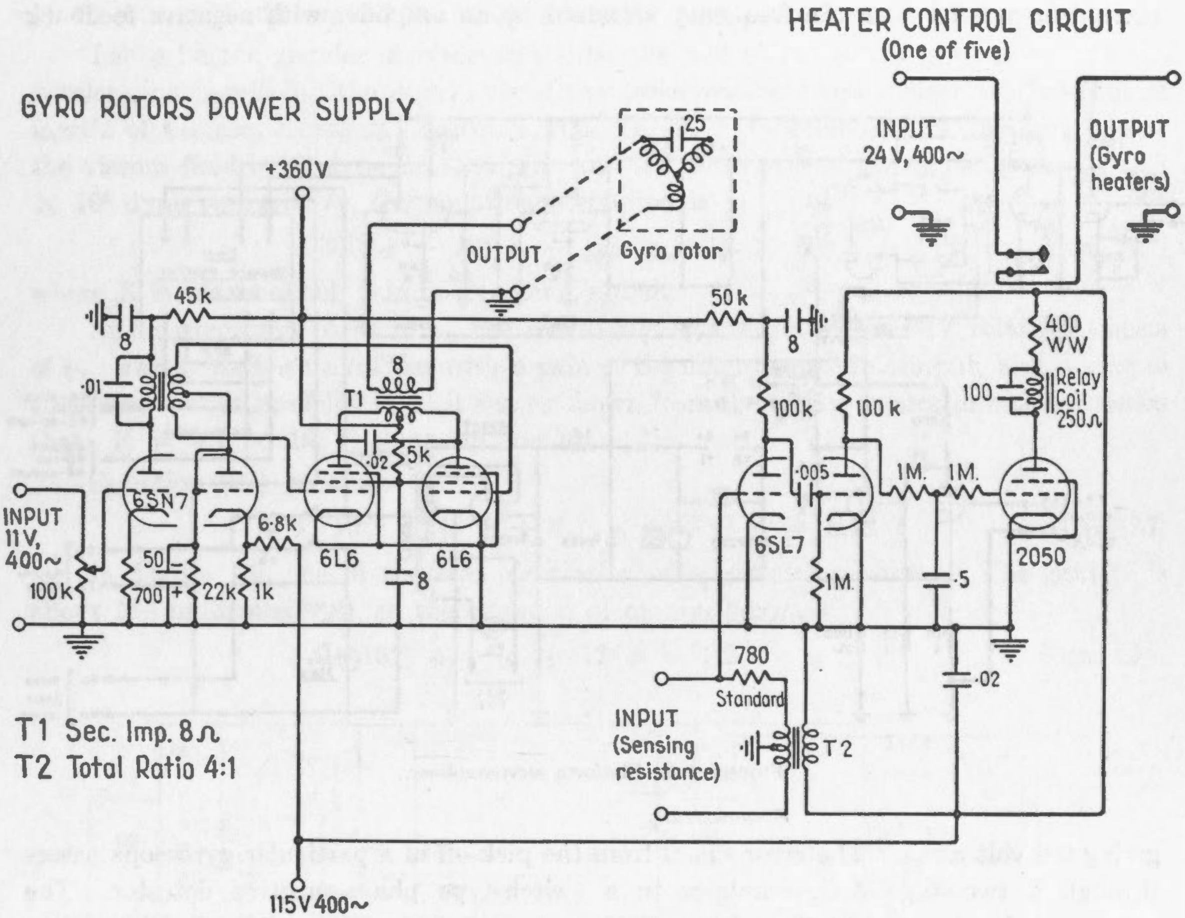


FIGURE 1.7.—Gyro rotor power supply and heater control circuit.

1.6.2 *Heater Control Circuits and Gyro Rotor Supply*

The temperatures of the gyroscopes and accelerometers are individually maintained at 165°F. by the heater control circuits shown in Figure 1.7. A temperature-sensing element in the unit is connected in a bridge circuit with a 780-ohm manganin resistor and a balanced transformer winding. The transformer is excited at 400 cycles, and the error signal of the bridge is amplified, rectified and applied to the control grid of a thyratron. The thyratron controls a relay which applies 400 cycle A.C. to a heater winding in the unit. When the temperature of the unit reaches 165°F., the resistor of the sensor is 780 ohms, the bridge balances cutting off the thyratron and the relay opens the heater circuit. The sensitivity of the circuit is limited by noise induced in the sensor winding to about 0.7°F. Warning lights supply a visual check on the operation of the heater units.

Power to operate the rotors of the three gyroscopes is supplied by a common class AB_2 push-pull power amplifier excited from the frequency standard. Each gyroscope has its own phase-splitting capacitor to give three phases from the single phase supply.

1.6.3 *The Platform Servoamplifiers*

Figure 1.8 shows the circuit of one of the three platform servoamplifiers with their common power supply and pick-off excitation amplifier. The gyroscope pick-offs are excited in parallel from the frequency standard by an amplifier with negative feedback

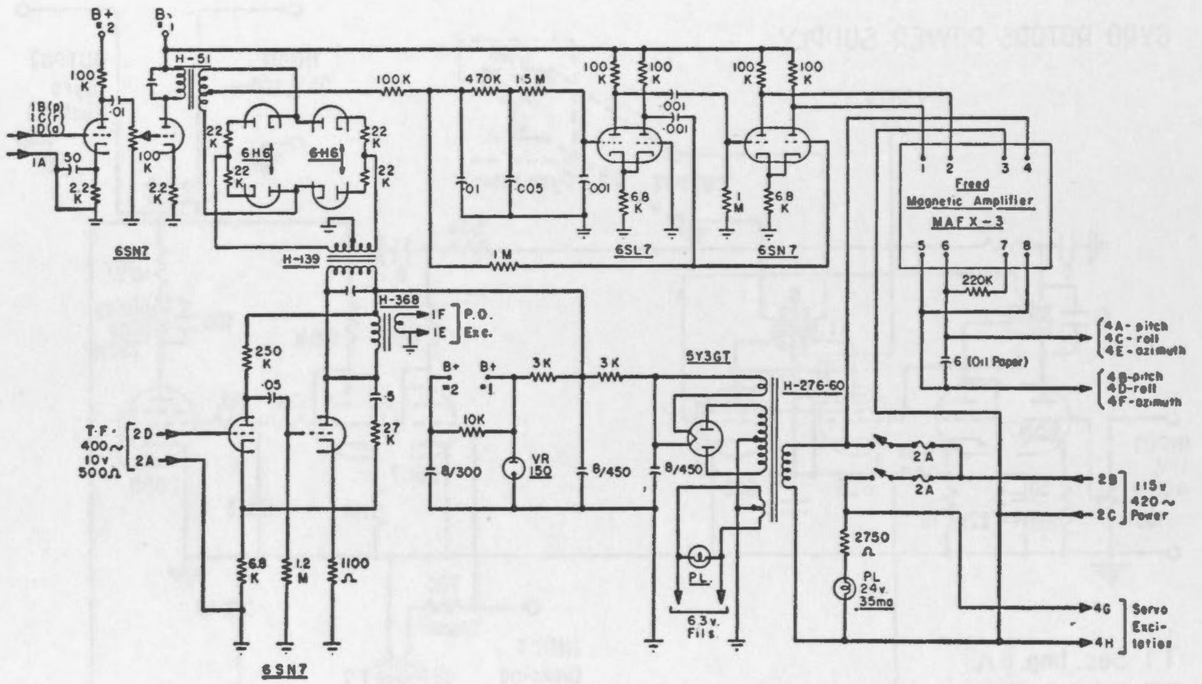


FIGURE 1.8—Platform servoamplifier.

giving 0.5 volt r.m.s. The error signal from the pick-off of a particular gyroscope passes through a two-stage A.C. amplifier to a switch-type phase-sensitive detector. The output of the detector is filtered and applied to two balanced amplifiers. The output of the first of these amplifiers is added, through an A.C. coupling network with a time constant of 1 millisec. to the output of the phase-sensitive detector at the grids of the second amplifier. The first amplifier thus introduces a phase advance of about 40 millisec. accompanied by a lag of 1 millisec.—corresponding to a phase-advance network with M = 40 (section 1.4). The filter following the phase-sensitive detector adds another lag of about 3 millisec. The plates of the second amplifier are connected to the control winding of a fast-response magnetic amplifier. A small amount of negative feedback is introduced around the magnetic amplifier (by the 220 K resistor) to increase its linearity and stability. The servoamplifier gives its full output of 10 watts into one winding of the servomotor for a steady input signal of 40 millivolts when the gain is adjusted for 3×10^{10} dyne cm./rad. The other winding of the servomotor is connected across the 115-volt 400-cycle line.

1.6.4 *The Accelerometer Control Circuits*

The accelerometers (Minneapolis-Honeywell HAU) are similar to the HIG gyroscopes except that, instead of a gyroscope rotor, the floated can contains a mass displaced from the axis of rotation of the can. The output signal of the pick-off is amplified and applied to the torque generator to produce a torque which tends to maintain the pick-off in its null position. When the accelerometer is subjected to an acceleration parallel to its axis of sensitivity, the torque necessary to accelerate the off-centre mass is supplied by the torque generator, and the torque generator current is a measure of the acceleration.

Let ϕ be the angular displacement from the null of the signal generator when the acceleration parallel to the input axis of the accelerometer is $g\delta$. Since the moment of inertia of the accelerometer element is 300 gm. cm.², the coefficient of damping due to the viscous fluid is 10^5 dyne cm./rad./sec. and the sensitivity of the accelerometer is 1.18 $\times 10^5$ dyne cm./gravity, the equation of motion is

$$300\,\ddot{\phi} + 10^5\,\dot{\phi} + K\phi = 1.18 \times 10^5\,\delta \qquad \text{Eqn. (22)}$$

where K is the feedback gain in dyne cm./radian.

At an excitation of 55 m.a., the sensitivity of the pick-off is 18.7 volts per radian of ϕ. For a feedback amplifier with a gain of G milliamps per volt input, and a torque generator excitation of 100 m.a., it can be shown from the torque generator characteristics that $K = 4.7 \times 10^3$ G dyne cm./radian.

Equation (22) becomes

$$3 \times 10^{-3}\,\ddot{\phi} + \dot{\phi} + 4.7 \times 10^{-2}\,G\,\phi = 1.18\,\delta \qquad \text{Eqn. (23)}$$

In Figure 1.9, one of the two identical control circuits is shown. The gain G is about 250 milliamps/volt, so the equation of motion becomes

$$3 \times 10^{-3}\,\ddot{\phi} + \dot{\phi} + 12\,\phi = 1.2\,\delta \qquad \text{Eqn. (24)}$$

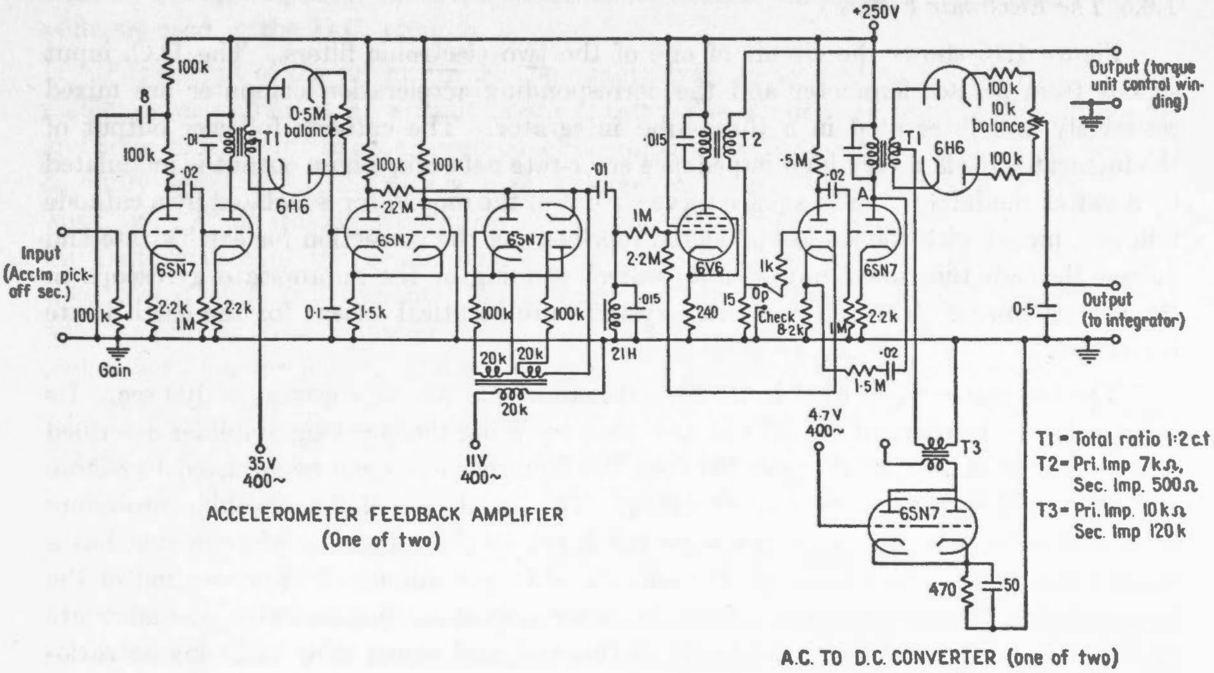


FIGURE 1.9.—Accelerometer control circuit.

The accelerometer is required to have a range corresponding to $-5° < \delta < +5°$. At the maximum accelerations, ϕ becomes 30 minutes of arc. The longer time constant of the accelerometer system is 80 milliseconds. When a higher gain was used the feedback loop became unstable because of amplifier lags.

When $\delta = 1$ minute of arc, the minimum detectable acceleration in which we are interested, $\phi = 0.1$ minute and this corresponds to an in-phase signal of 0.7 millivolt against a total noise background of 30 millivolts. It is necessary therefore to amplify, convert to D.C., amplify and modulate the output. The output current in the control winding of the torque generator passes through a 15-ohm resistance. The in-phase voltage across this resistance is proportional to the acceleration being measured.

The 6V6 output tube can deliver a maximum output of 60 milliamps corresponding to a torque of 1.5×10^4 dyne-cms. or $\pm 7.3°$ of δ. This range of acceleration was quite satisfactory in this application. The null voltage across the control winding was 0.1 volt quadrature and second harmonic. Provision was made in the circuit for a balancing adjustment. A small feedback ratio across the 6V6 helps stabilize the phase of the 400-cycle voltage across the 15-ohm resistance.

This 400-cycle voltage proportional to acceleration is amplified by an amplifier whose gain is stabilized by negative feedback, and converted to D.C. by a phase-sensitive detector supplied with a large reference voltage for linearity. One minute of δ is equivalent to an in-phase voltage of 2.06 millivolts across the 15-ohm resistance, and the gain was adjusted by feedback so that this produced 100 millivolts D.C. at the output of the phase-sensitive detector. The output was a linear function of the input to $\pm$ 30 volts ($\delta = \pm 5°$), after which the gain decreases. At the maximum output of $\pm$40V, the gain has decreased by 15 per cent. Provision was made for zeroing the acceleration output circuits.

1.6.5 *The Electronic Filters*

Figure 1.10 shows the circuit of one of the two electronic filters. The D.C. input signals from an accelerometer and the corresponding acceleration computer are mixed resistively and integrated in a three-tube integrator. The cathode follower output of the integrator feeds a very high impedance error-rate network, whose output is modulated by a switch modulator. The square wave output of the modulator is isolated by a cathode follower, mixed with the sinusoidal signal representing the correction for earth's rate and passed through the tuned torque-unit control winding of the appropriate gyroscope in the correct phase. The roll and pitch systems are identical except for the earth's rate correction.

The integrator when used in its normal manner has a time constant of 100 sec. Its input grid can be checked for drift at any time by using the checking amplifier described later. A balancing potentiometer between the input cathodes can be adjusted to restore the input grid voltage to zero on checking. The sensitivity of this checking procedure is 10 millivolts, which is sufficient since the input to the integrator after mixing has a value corresponding to a scale of 50 millivolts D.C. per minute of arc deflection of the apparent from the true vertical. In flight, after a short settling period it was adequate to check the zeros of all the D.C. circuits of this sort, and adjust their balancing potentiometers accordingly, about once each hour. Laboratory tests on this D.C. circuit showed

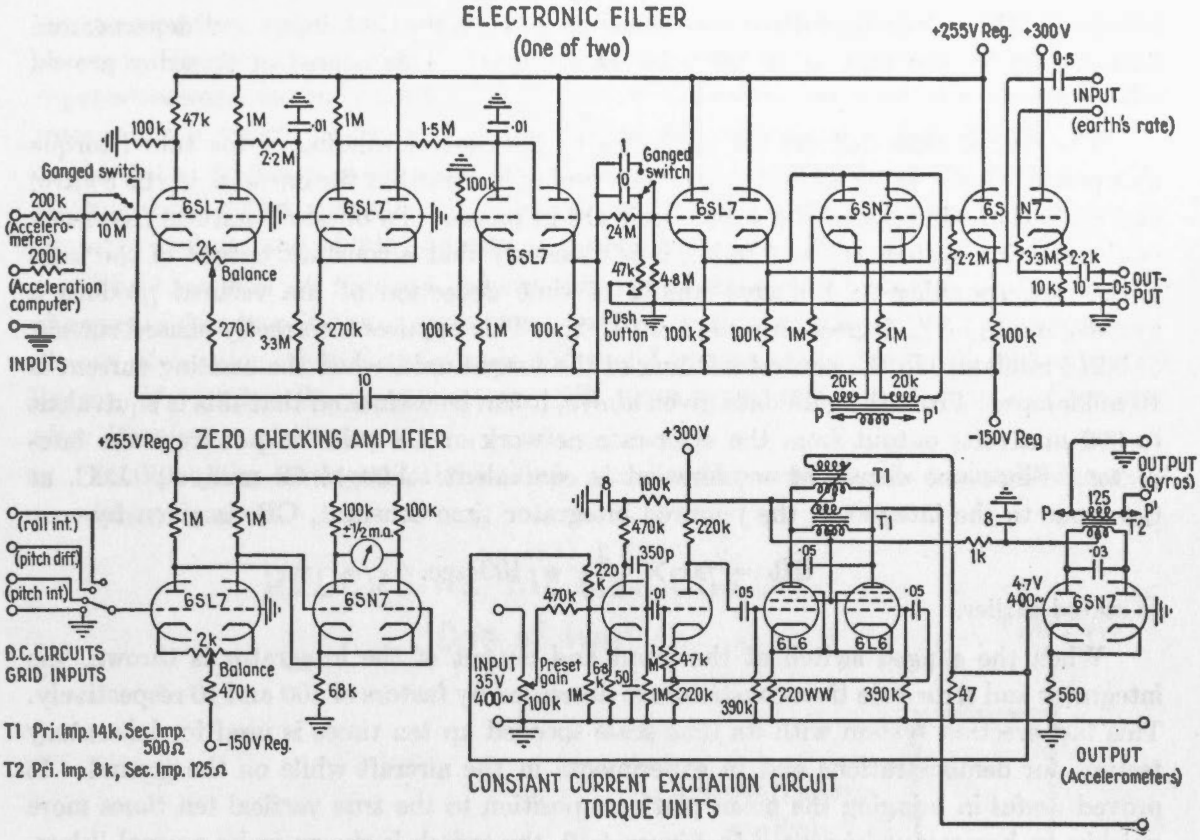


Figure 1.10.—Electronic filter and constant current excitation circuit.

that a 10 per cent change in heater voltage produced a cathode potential change of about 4 mV. Voltage regulator tubes are adequate to regulate the positive and negative supply voltages used in the D.C. circuits.

The output of the integrator can be qualitatively monitored on a ± 50 V panel voltmeter, or measured at an output check point. The condensers used in the integrator and error-rate circuits to obtain long time constants were 10 microfarad oil-filled condensers, carefully selected for their very high leakage resistance and freedom from condenser 'soaking'. Their leakage resistances are greater than 10^9 ohms. and no deterioration in the performance of the condensers was found over three years. No difficulties were encountered with grid currents, but leakage across the input tube pins in very humid weather proved troublesome at first. This leakage was eliminated by cleaning the tube socket very thoroughly, and taking great care in soldering the socket connections.

The maximum output of the integrator is ± 40 volts; since the time constant is 100 secs., the integrator is easily capable of handling accelerations of 2 degrees lasting for 2 minutes, which are the maximum accelerations normally found in flight. The required output is

$$120 \int_0^{120} \frac{50 \times 10^{-3}\ dt}{100} = 7.2 \text{ volts.}$$

The error-rate network is straight-forward, with its time constant of 240 secs. (corresponding to $a\omega_n = \frac{1}{4}$ per minute) and D.C. gain of $\frac{1}{6}$ (corresponding to $a/b = \frac{1}{4}/\frac{3}{2} = \frac{1}{6}$). To avoid loading the network, the switch modulator was fed from a cathode follower. The switch modulator was linear to ± 15 volts D.C. input and departs from linearity by 12 per cent at ± 30 volts D.C. input. This degree of linearity proved adequate.

The output tube delivers 2.0 milliamps to the control winding of the tuned torque unit per volt input at its control grid. The tuning is such that the currents in the control and excitation windings of the torque unit are in phase. To obtain a natural frequency of the erection system $\omega_n = 1/\text{min.}$, it is necessary that a constant output of the integrator corresponding to 1 degree-minute of time deflection of the vertical produce a gyroscope rate of $^a/_b$ degrees/minute, i.e. 10°/hr. This requires a correctly phased current of 0.216 milliamp. in the control winding of the torque unit, when the exciting current is 10 milliamps. From the gain data given above, it can be estimated that this is equivalent to 300 millivolts output from the error-rate network or 1.8 volts output from the integrator. Since one degree of acceleration is equivalent to 60 × 50 millivolts D.C. at the input to the integrator, the required integrator time constant, CR, is given by

$$CR = 60 \times \frac{3}{1.8} = 100 \text{ sec.}$$

as stated earlier.

When the ganged switch at the input and output of the integrator is thrown, the integrator and error-rate time constants are decreased by factors of 100 and 10 respectively. This fast-erection system with its time scale speeded up ten times is used for laboratory testing, for demonstrations and in experiments in the aircraft while on the ground. It proved useful in bringing the mean platform position to the true vertical ten times more quickly on becoming airborne. In Figure 1.10, the switch is shown in its normal "slow-erection" position. The integrator time constant must be changed by 10^2 (rather than changing the gain of the torque unit amplifier for instance) so that when the system has reached equilibrium the output of the integrator will be at the proper level when the switch is thrown to "slow-erection".

In order to avoid transients in the system due to the apparent change in rate of the platform gyroscopes when the heading of the aircraft changes, torques are applied to

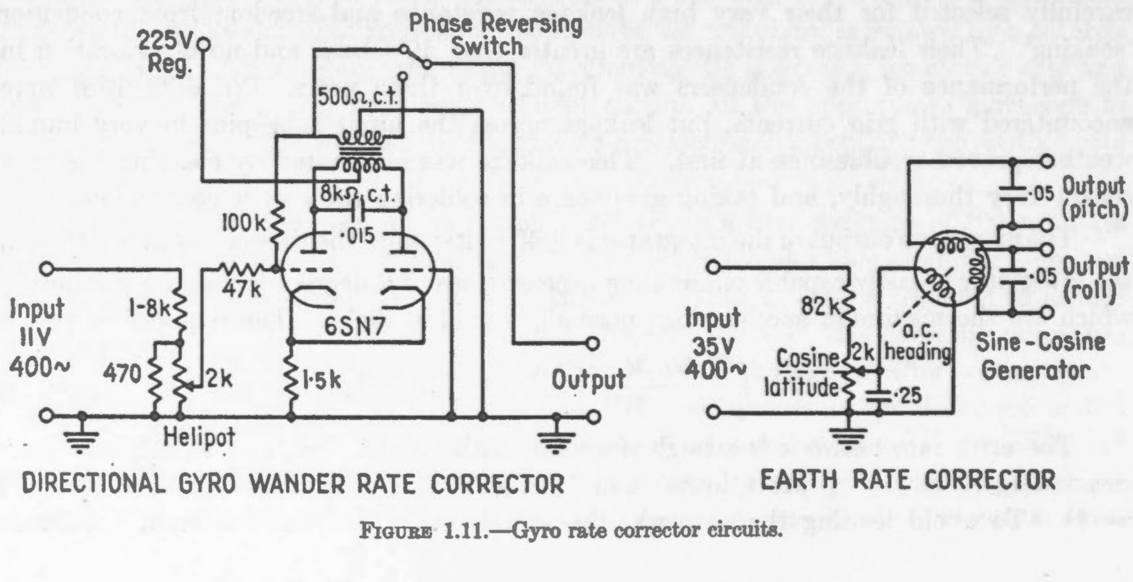


FIGURE 1.11.—Gyro rate corrector circuits.

the gyroscopes proportional to the components of the earth's rotation. The method is shown in Figure 1.11. A 400-cycle voltage proportional to the cosine of latitude ϕ, from a potentiometer manually set to the latitude, is applied to the rotor of a resolver. The rotor shaft is set manually to the heading of the aircraft, ψ. The voltages induced in the stator windings, $\omega \cos \phi \sin \psi$ and $\omega \cos \phi \cos \psi$, are added to the outputs of the pitch and roll filters respectively. The resolver windings are tuned to minimize potentiometer loading, and obtain the correct phase of the outputs.

The curve $h_e(t)$ of Figure 1.5 shows the type of transient which would occur on large changes of heading if these corrections for the earth's rotation were not applied. A change of heading of 180° at latitude 45° would produce a maximum platform error of $2\omega \cos 45° \times 1.3 = 28$ minutes of arc. The error would reduce to 1 minute of arc only after 10 minutes of time.

In flight, the settings of the latitude and heading controls are maintained correct to within 5° or so.

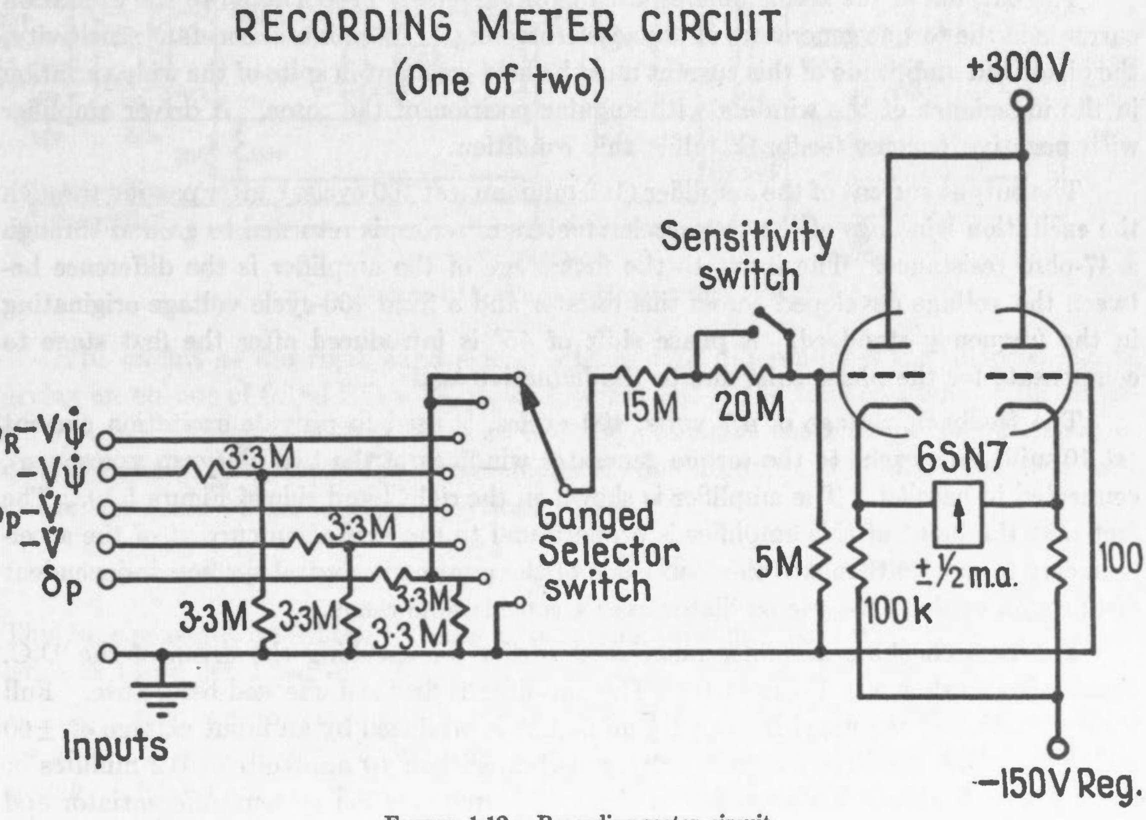


FIGURE 1.12.—Recording meter circuit.

1.6.6 *The Recording Meter Circuits*

The input signals to the electronic filters are recorded by means of two Esterline-Angus Strip Chart meters. The chart drives are mechanically coupled and operate at $\frac{3}{4}$ inch per minute. Figure 1.12 shows one of the two meter amplifiers.

A selector switch at the input of the amplifiers allows recording of 8 different combinations of signals δ_p, δ_r, $-\dot{V}$, $-V\dot{\psi}$, $\delta - \dot{V}_p$, $\delta_r - V\dot{\psi}$, using the notation of section

1.5. Two sensitivities are provided, corresponding to meter ranges of $\pm 5°$ of δ and $\pm 2\frac{1}{2}°$ of δ. Linearity, accuracy of scale adjustment ($\pm 3\%$), and zero stability are satisfactory.

These meter records are very important in the evaluation of the platform performance. It is possible to examine them to determine the performance of the acceleration computation and correction methods used, to investigate platform transient response and to estimate the accuracy of stabilization to about five minutes of arc under steady flight conditions. In the positive identification of magnetic anomalies, this is very helpful.

It should be clear that such records constitute the data upon which the design of this stabilizing system can best be modified; the choice of the natural frequency of the gyroscope erection system depended on the spectrum of long period accelerations deduced from the records obtained using an earlier model (6, 7) of the stabilized platform.

1.6.7 *The Torque Generator Excitation Circuit*

The outputs of the accelerometer circuits are inversely proportional to the excitation currents in the torque generators of the accelerometers. To maintain constant sensitivity, the phase and amplitude of this current must be held constant in spite of the wide variation in the impedance of the winding with angular position of the rotor. A driver amplifier with negative current feedback fulfils this condition.

The output current of the amplifier (100 milliamps at 400 cycles), after passing through the excitation windings of the two accelerometers in series, is returned to ground through a 47-ohm resistance. The input to the first stage of the amplifier is the difference between the voltage developed across this resistor and a fixed 400-cycle voltage originating in the frequency standard. A phase shift of 45° is introduced after the first stage to compensate for the phase shift due to the inductive load.

The feedback voltage of 4.7 volts, 400 cycles, is used to provide excitation current (at 10 milliamps each) to the torque generator windings of the two platform gyroscopes, connected in parallel. The amplifier is shown on the right hand side of Figure 1.10. The fact that the input of this amplifier is proportional to the excitation current of the accelerometer torque units makes the loop gains of the gyroscope control systems independent of the level of the 400-cycle oscillator over a considerable range.

The zero checking amplifier mentioned earlier for checking the drifts of the D.C. circuits is also shown in Figure 1.10. The amplifier is first self checked before use. Full scale deflection of the panel meter ($\pm\frac{1}{2}$ milliamp) is produced by an input voltage of ± 60 millivolts. The sensitivity of zero settings is better than 10 millivolts or 0.2 minutes of arc. A switch allows this amplifier to check the pitch erection system differentiator and integrator, and the roll system integrator. The action of checking does not disturb the operation of the circuit being checked.

1.6.8 *The Pitch Acceleration Computer*

If wind velocity is neglected, the fore-and-aft component of the acceleration of the aircraft is simply $\dot{V}$, the rate of change of airspeed. This approximate acceleration is automatically computed as a D.C. voltage, and subtracted from the pitch accelerometer output by the resistive network at the input to the pitch system integrator.

Airspeed is supplied continuously to the acceleration computer by a Kollsman True Airspeed Meter (Type 1239 B-O-4) in the form of a synchrotel output signal with a sensitivity of 36°/100 knots and a range of 0 to 650 knots. The shaft of a 10-turn precision potentiometer with a resolution of 1 part in 10,000 is driven by a servomotor and autosyn combination to follow this signal at a ratio of 10.8°/knot. Since a steady D.C. potential of 105 volts is applied across the potentiometer, a D.C. signal proportional to the airspeed, at 0.186 volt/ft./sec. is obtained at the slider of the potentiometer.

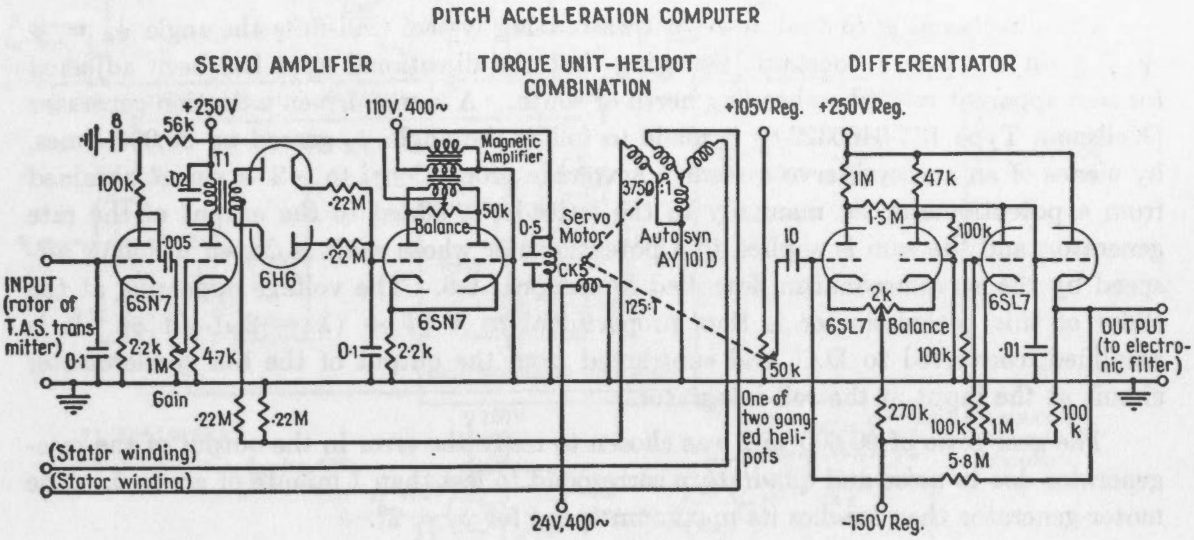


FIGURE 1.13.—Pitch acceleration computer.

The circuit at the right hand side of Figure 1.13 differentiates the airspeed signal, giving an output of 0.186 RC volts/ft/sec.², where RC is the time constant of the differentiator in seconds. The time constant is chosen to make the scale of the differentiator output equal to the scale of the accelerometer circuit output, i.e. 100 millivolts per minute of arc deflection of the apparent vertical. Thus

$$0.186\ \mathrm{RC} \times 32 \times \frac{2\pi}{360 \times 60} = 0.100, \text{ or RC} = 58 \text{ sec.}$$

This time constant was obtained using a 10-microfarad condenser with the same characteristics as those described earlier.

The servo system has a natural frequency of about 1 c.p.s., and is critically damped for a voltage gain of 300, or about one half of maximum. The helipot resolution corresponds to 0.03 knot and is adequate. The 0.1-microfarad condenser across the rotor of the synchrotel transmitter ensures zero reaction in all positions of the rotor shaft.

It will be noticed that instead of applying differentiated airspeed to the input of the integrator a signal proportional to airspeed could have been subtracted directly from the output of the integrator. Although the present system makes a smaller demand on the operating range of the integrator, the advantage is in fact unimportant, since the integrator can easily handle the accelerations of normal flight. However, the method adopted has the advantage that it allows the recording of the estimated and measured pitch accelerations under different flight conditions. A great deal was learned about the usefulness of this type of correction from a comparison of these records, as is discussed later. Furthermore, difficulties about the D.C. level of operation of the pitch control system were avoided by using a differentiator.

1.6.9 *The Roll Acceleration Computer*

The component of acceleration about the roll axis of the aircraft, if wind is neglected, has been proved equal to V $[\dot{\psi} + (\dot{\lambda} - 2\omega) \sin \phi]$ in the notation established earlier in the theoretical discussion (section 1.5).

The directional gyro dual autosyn transmitting system transmits the angle $\psi_g = \psi + \int \dot{\lambda} \sin \phi \, dt$ + a constant, assuming that the directional gyro has been adjusted for zero apparent rate when heading north or south. A motor-driven induction generator (Kollsman Type 133-0460322-0) is made to follow the angle ψ_g geared up 90,000 times, by means of an autosyn servo system. A voltage proportional to $-2\ \omega \sin \phi$, obtained from a potentiometer set manually to the latitude, is added to the output of the rate generator, and the sum is applied to a potentiometer whose shaft is driven to follow airspeed by the servomechanism described in section 1.6.8. The voltage appearing at the slider of this potentiometer is thus proportional to V $[\dot{\psi} + (\dot{\lambda} - 2\omega) \sin \phi]$. It is amplified, converted to D.C. and subtracted from the output of the roll accelerometer circuit at the input of the roll integrator.

The gear ratio of 90,000 to 1 was chosen to make the error in the output of the rate-generator due to noise and quadrature correspond to less than 1 minute of arc in δ. The motor-generator then reaches its maximum speed for $\delta = 7°$.

Figure 1.14 shows the complete roll acceleration computer circuit. Considerable care was required in damping the rate-generator servo system to make it follow smoothly the wide range of angular velocities it must handle. Damping was obtained by adding to the autosyn error signal a rate signal from the generator. Since the autosyn system operates at line frequency and the generator is excited from the frequency standard, the two signals are demodulated before mixing at the grids of the tube controlling the magnetic amplifier which drives the motor-generator. The correction $- 2\omega \sin \phi$ is introduced by the potentiometer labelled "Coriolis Correction", which is graduated in latitude from 30° to 90°.

The temperature coefficient of the rate-generator is between −0.2 and −0.3 per cent per C° in the range 10°C to 70°C. Since the greater part of the computer output is periodic, the steady component amounting to only a few minutes of arc in δ, temperature changes have a negligible effect on the accuracy of the platform.

Figure 1.14 also shows the automatic cut-out circuit. Both the roll accelerometer circuit and the roll acceleration computer saturate with accelerations of $\pm 7°$ in δ. The input to the integrators is grounded automatically by the cut-out circuit whenever the roll acceleration exceeds this value to avoid developing large transients in the stabilization system during major changes of heading. The A.C. output signal of the roll accelerometer is applied to a negatively biassed detector. When the output of the detector is positive, the thyratron closes the relay, cutting off the input to both the roll and pitch integrators. A release time constant of 8 seconds is provided to allow the aircraft to settle on its new heading after the turn is completed. This cut-out is very important

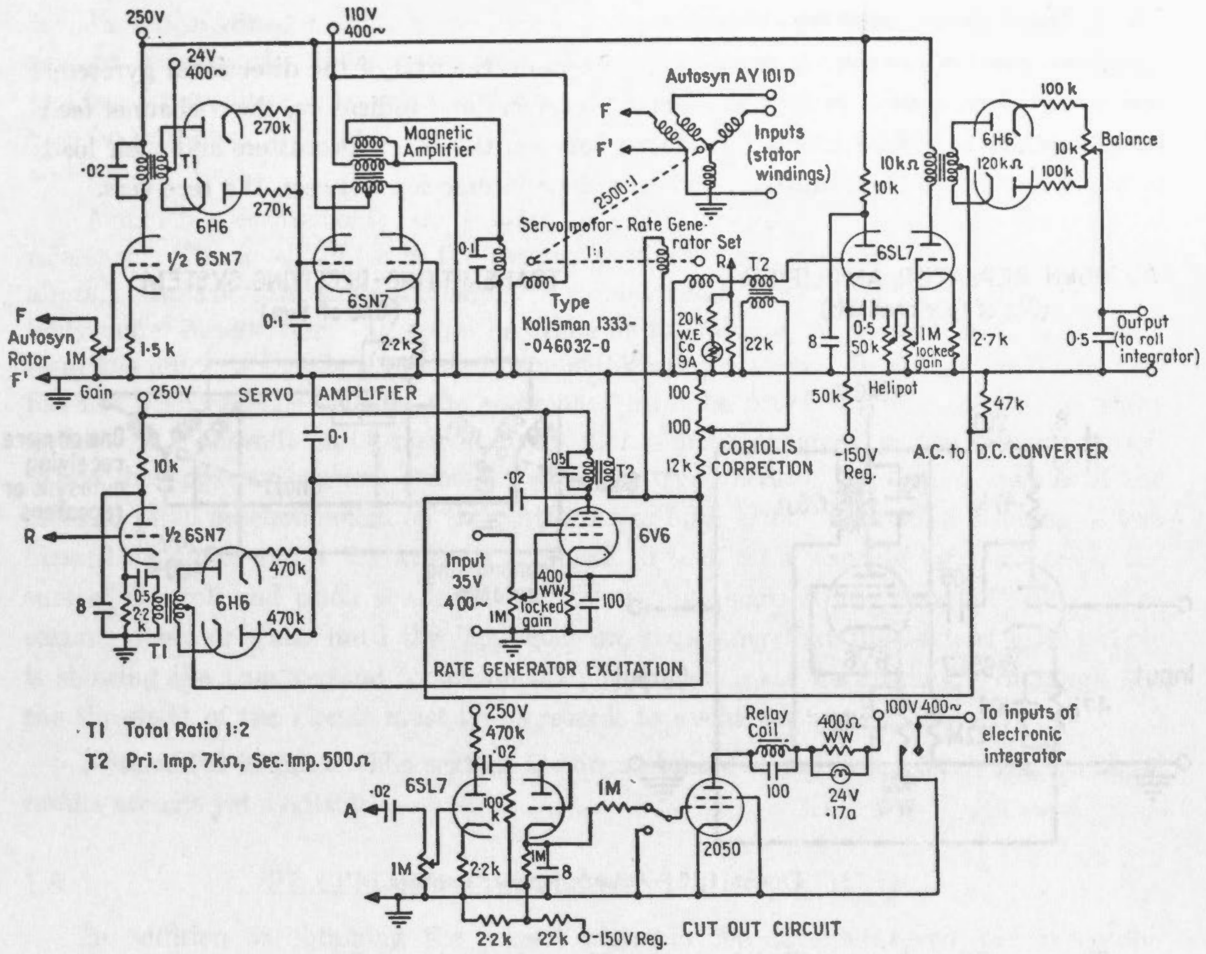


FIGURE 1.14.—Roll acceleration computer and cut-out circuit.

since without it, a turn of 180° in one minute would produce a transient reaching a maximum error value of about 4°, and 9 minutes later the platform could still be 7 minutes in error.

1.6.10 *The Directional Gyroscope Rate Corrector*

The directional gyro, unlike the roll and pitch gyros, is not provided with automatic control of its rate. It is allowed to wander, and the corrections to be applied to its readings are determined at 10 or 15 minute intervals. However, its rate must be kept at less than 5° per hour to avoid introducing errors of 1 minute of arc into the platform through the roll acceleration computer. A low rate also makes reduction of the magnetic declination results easier.

A calibrated control is provided to apply a torque to the directional gyro and change its rate by a known amount up to a maximum of ± 140° per hour. The circuit shown on the left-hand side of Figure 1.11 applies the calibrated voltage to one winding of the directional gyro torque generator. The other winding is excited at 10 m.a. by the constant current source described in section 1.6.7.

1.6.11 *The Autosyn Repeater Amplifiers*

Since the 1:1 and 36:1 autosyn transmitters on the axis of the directional gyroscope turntable are connected to several different receivers and indicators, the 4-channel feed-back amplifier of Figure 1.15 is introduced between the two transmitters and their loads to avoid loading the transmitters, and to reduce interaction between the receivers.

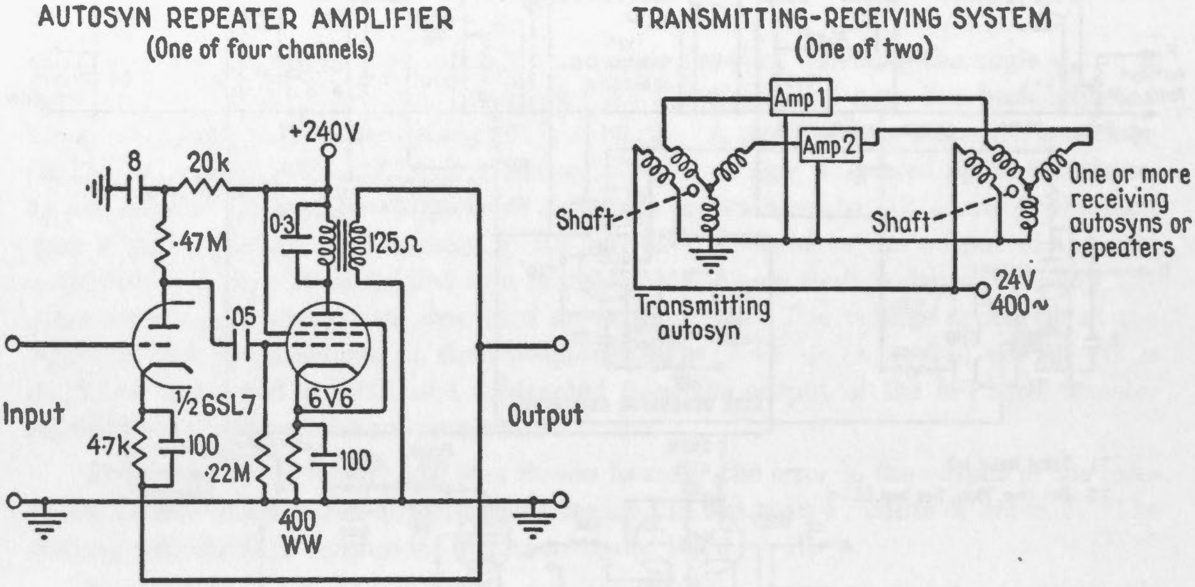


FIGURE 1.15.—Autosyn repeater amplifier.

The amplifier shown will drive two self-synchronizing indicators and two receivers with maximum errors of 1°, corresponding to less than 2 minutes of arc when the 36:1 gear ratio is considered.

The condensers across the primary windings of the output transformers are required to prevent high frequency oscillation.

1.7 THE SYNCHRONOUS PERISCOPIC SEXTANT

The corrections to be applied for drift of the directional gyroscope are determined in flight by measuring, every 10 or 15 minutes, the angle in azimuth between the axis of the directional gyro and the sun or a star. This is done with a periscopic sextant (Kollsman Type 1471C-01), whose mount (Kollsman Type 1708-01) has been modified by the addition of a servomotor, a gear train, and an autosyn. The servo system keeps the index of the graduated circle in the mount parallel to the axis of the directional gyro, using the 36 to 1 autosyn, independent of yawing of the aircraft. When the observer looks into the eyepiece of the sextant, he sees an image of the sun, the sextant level bubble and cross-hairs, and a segment of the graduated circle. The angle read on the graduated circle is the angle between the gyroscope axis and the sun.

In the modified mount, a mechanical connection is also provided to stabilize the sextant in azimuth. This stabilization helps greatly in obtaining accurate readings, and enables readings to be taken under broken cloud when observations would not otherwise be possible. A tangent screw for adjusting the sextant in azimuth helps in setting and reading to 0.2°.

Azimuth measurements are subject to errors arising from errors in the vertical reference. The level bubble in the sextant is affected by horizontal accelerations of the aircraft, and azimuth errors of a degree or so may result, depending on the altitude of the body under observation. It would be desirable to stabilize the sextant in roll and pitch from the autosyn signals available in the stabilized platform. In the present case, this has not been possible because the equipment must be fitted into any aircraft on short notice. A makeshift stabilization, in effect, has been achieved in the following way. When the apparent vertical coincides with the true vertical, the output signals of the roll and pitch accelerometers on the platform are both zero. A circuit consisting of two biassed detectors and a thyratron is arranged to turn on a warning light whenever the sum of the roll and pitch accelerations (disregarding sign) is less than 0.1° of δ. The sextant operator waits until the light goes on, indicating that the sextant level-bubble is showing the true vertical to within 0.1°, and then takes his reading. In rough air, the threshold of the circuit must be increased, to avoid waiting indefinitely.

Note added in proof: The sextant is now stabilized in roll and pitch. Experimental results are not yet available.

1.8 PLATFORM ALIGNMENT PROCEDURES

In addition to obtaining the correct phase in the different servo and gyroscope control loops, and the correct voltage relationships throughout the gyroscope erection systems, a number of other preliminary adjustments were required. These included:

(i) The alignment of the two autosyns on the directional gyroscope turntable shafts;

(ii) the adjustment of the parallelogram linkage system in the way described earlier;

(iii) the adjustment of the roll tangent screw at the magnetometer yoke. This was made by pitching the system and looking for errors about the roll axis between the level bubble in the direction gyroscope turntable and the one on the magnetometer head. An accuracy of adjustment about the roll axis of 0.5° is easily adequate.

The platform gyroscopes were rotated in their mounting clamps so that their sensitive axes were parallel to the axes of roll and pitch of the platform to within 15 minutes of arc. The lean of each accelerometer is defined as the angle between the jewelled axis of the accelerometer and the turntable axis. The clamps were adjusted so that these angles were less than 1 minute of arc for both accelerometers.

Great care was taken that the signals introduced for the Coriolis and earth's rate corrections were in the correct phase.

1.9 POST-FLIGHT ANALYSIS OF THE PLATFORM RECORDS

A number of conclusions were reached from an examination of the fifty hours of records obtained during the 1953 field season;

(i) in very bumpy air, the $\dot{V}$ correction should not be introduced because of overshooting of the airspeed transmitter and turbulance around the pitot head.

(ii) in smooth flight, the magnitude of the longer period accelerations, $(\delta_p - \dot{V})$, is about one half to one third that of δ_p. At times the correction can be almost perfect; e.g. in Figure 1.16, a tracing of δ_p and $-\dot{V}$ records taken during a flight on September 5th, 1953, is shown. The smoothed record of $-\dot{V}$ is nearly equal to the image of δ_p, and during the twenty minute interval $(\delta_p - \dot{V})$ consisted of very low amplitude, high frequency signals which are easily filtered by the pitch control system.

(iii) the improvement in platform accuracy using the roll acceleration computer is obvious. Figure 1.17 shows tracings of δ_r and $(\delta_r - V\dot{\psi})$ over a typical 20-minute interval. Corrections to the aircraft's course such as are made in flight every 20 minutes or so are seen at A and C, and at B a turn of 40° occurred. At A and C the input signals to the roll erection system $(\delta_r - V\dot{\psi})$ show that the platform must remain very close to the true horizontal with the long period (6.3 minutes) control system used. The amplitude of any forced oscillation of the system is negligible, even while the heading is changing. Without the centrifugal acceleration computer, magnetic observations in the 5-minute periods after the turns at A and C would require corrections for forced oscillations of the platform. At B, the turn of 40° was made so slowly that the relay did not cut off the signals to the roll and pitch integrators. The turn was also made without an adjustment of the earth's rate corrector. The big improvement in transient response is again seen: the next 5 minutes of magnetic records did however require critical examination, since the acceleration compensation was not perfect.

It is concluded that the additional complexity required for computing estimates of acceleration and correcting for these estimates is justified for a three-component airborne magnetometer. The estimation of centrifugal accelerations during turns is essential to the efficient operation of the instrument.

The records obtained in the 1954 field season confirm the conclusions listed above. The only difficulties are those associated with apparently false short-period signals from the airspeed transmitter, and these do not affect platform performance.

1.10 A DISCUSSION OF PLATFORM ERRORS

Errors in the system are primarily due to aircraft accelerations. If the aircraft flies along a great circle at constant speed the principal acceleration term vanishes, but a correction for the horizontal component of the Coriolis component of acceleration is still required. The Coriolis correction has been allowed for, and navigational turning accelerations or centrifugal accelerations associated with the curvature of rhumb-lines compensated in the roll acceleration computer. For a North Star aircraft, flying east

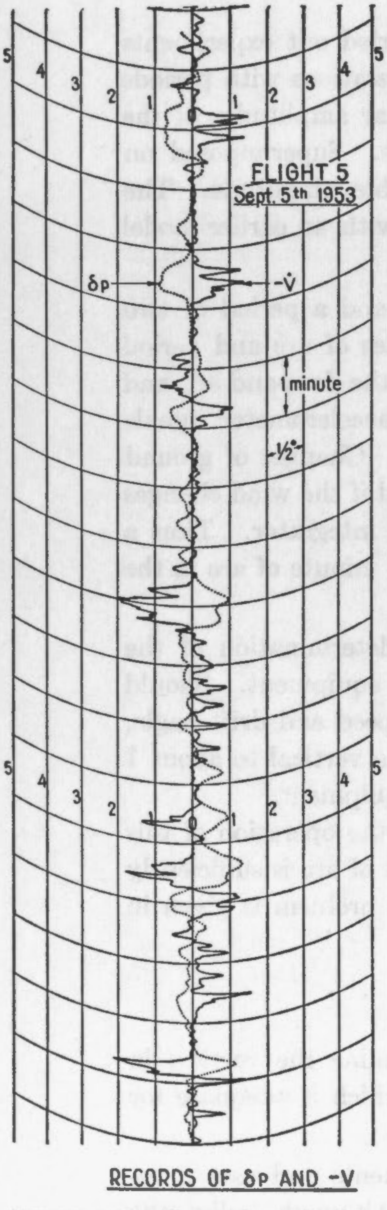


FIGURE 1.16.—Comparison of pitch accelerometer output and computed acceleration.

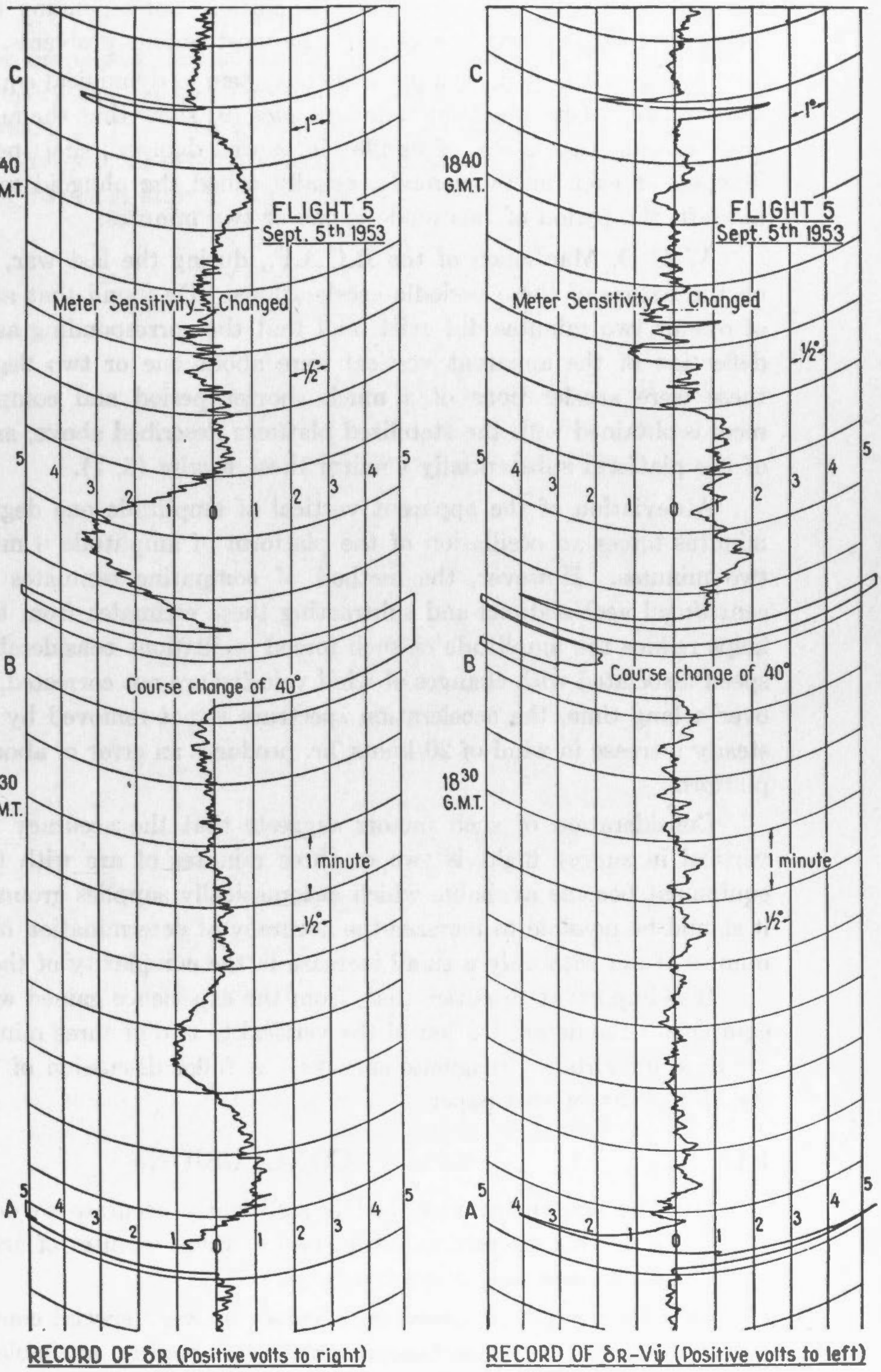


FIGURE 1.17.—Comparison of roll accelerometer output and input to roll integrator.

over Ottawa the Coriolis correction is about 3.5 minutes of arc, and the convergency term in the roll acceleration computation compensates for the rhumb-line correction of 0.5 minute of arc. Consequently accelerations corresponding to random alterations of course and fluctuations in speed are the most serious problems.

An aircraft in flight is a mechanical system in dynamical equilibrium with the earth's atmosphere. Text books on aerodynamics (9) show that the angular motions of an aircraft contain two modes of oscillation, a well damped, short-period mode and a poorly damped or even unstable mode, usually called the phugoid mode. For a North Star aircraft, the period of this mode is one or two minutes.

W/C D. MacLulich of the R.C.A.F., during the last war, carried out experiments on the nature of these periodic accelerations. He found that accelerations with periods of one or two minutes did exist, and that the corresponding angular amplitudes of the deflection of the apparent vertical were about one or two degrees. Superimposed on these were accelerations of a much shorter period and comparable amplitude. The records obtained with the stabilized platform described above, and with an earlier model of the platform substantially confirm these results (6, 7).

A deviation of the apparent vertical of amplitude one degree and a period of two minutes forces an oscillation of the platform of amplitude 6 minutes of arc and period two minutes. However, the method of computing estimates of the fore-and-aft and centrifugal accelerations and subtracting these estimates from the accelerometer signals helps reduce the amplitude of such forced oscillations considerably. Changes of ground speed associated with changes of wind velocity are not corrected, and if the wind changes over a long time, the acceleration spectrum is not removed by the integrator. Thus a steady increase in wind of 20 knots/hr. produces an error of about 1 minute of arc in the platform.

Consideration of such factors suggests that the accuracy of determination of the vertical in survey flight is two or three minutes of arc with this equipment. Should equipment become available which automatically supplies ground speed and drift angle, it should be possible to increase the accuracy of determination of the vertical to about 1 minute of arc with only a small increase in the complexity of the equipment.

It is important to notice that, from the experience gained with the operation of this equipment, the determination of the vertical to two or three minutes of arc is sufficiently accurate for airborne magnetic surveys. A fuller discussion of this problem is given in the third part of this paper.

1.11 CONCLUSIONS

(i) The equipment described is sufficiently accurate to determine the vertical in a moving aircraft to within two or three minutes of arc, which is adequate for large scale magnetic surveys.

(ii) The equipment described involves no very special components and uses gyroscopes, electromechanical units, etc. readily available. Although bulky the individual parts of the system are fundamentally simple and easy to maintain and service. The airborne serviceability record in three seasons of operation proved excellent.

(iii) It was found necessary to use first-order acceleration computers in order to obtain this degree of accuracy.

(iv) The gyroscope control system used, with its less severe demands on gyroscope performance than other proposed schemes, proved adequate for this application and reliable in operation, for periods of a hundred hours flying or more. It was found necessary to have the gyroscopes overhauled at the factory after each season. The reasons for this deterioration and its effect on the performances of the system are discussed later in this paper.

APPENDIX: THE ANGULAR COMPLIANCE OF HIGH FREQUENCY GEAR TRAINS

In computing the contributions to compliance, the following were estimated:

(i) torsion in the shafts. Elementary books on mechanics show that the torque T is related to the angle of twist by the relation

$$T = \frac{\pi\, a^4\, E_n}{2l}\,\theta$$

where E_n = modulus of rigidity,
a = radius of shaft of circular cross-section,
and l = length of shaft.

The contribution to compliance at the output shaft,

$$X_t = \sum_{\text{shafts}} \frac{\theta}{T} \cdot \frac{1}{N^2}$$

where N is the gear ratio to the output shaft.

Therefore $$X_t = \Sigma\, \frac{2l}{\pi a^4} \cdot \frac{1}{E_n N^2}$$

and in this design equals 2×10^{-7} rads./lb.in. approximately.

(ii) bending of the shafts. The bending of the shaft of the cast aluminum turntable can be estimated. If its deflection is Δ, the contribution to angular compliance is $X_d = \frac{\Delta}{2FR^2}$ where the bending force is 2F, and the radius of the internal gear is R.

Elementary books on mechanics show that for a cantilever loaded at one end and supported rigidly by the other $\frac{\Delta}{2F} = \frac{l^3}{3EI}$

where E = Young's modulus,
l = length of cantilever,
and I = second moment of inertia.

Therefore $X_d = \frac{l^3}{3EI\ R^2}$ and in this design equals 2×10^{-7} rads/lb.in. approximately. The contribution of the other shafts is much smaller.

(iii) deflection of the gear teeth.

A typical example of the calculation involved in estimating the deflection of external involute gear teeth is given below.

A two-inch diameter gear engages a half-inch pinion. Both gears are 48 pitch, and consequently 4 teeth are wholly or partially in contact. A parabolic section AOA (Figure 1.18) was assumed, and consideration of the number of teeth in contact suggested that a good approximation would be to regard the total force F on one tooth at the centre along the pitch circumference.

With the notation of Figure 1.18, the geometrical moment of inertia of the shaded area is $Ak^2 = \frac{bt^3}{12} \cdot \frac{(h - x)^{3/2}}{h^{3/2}}$.

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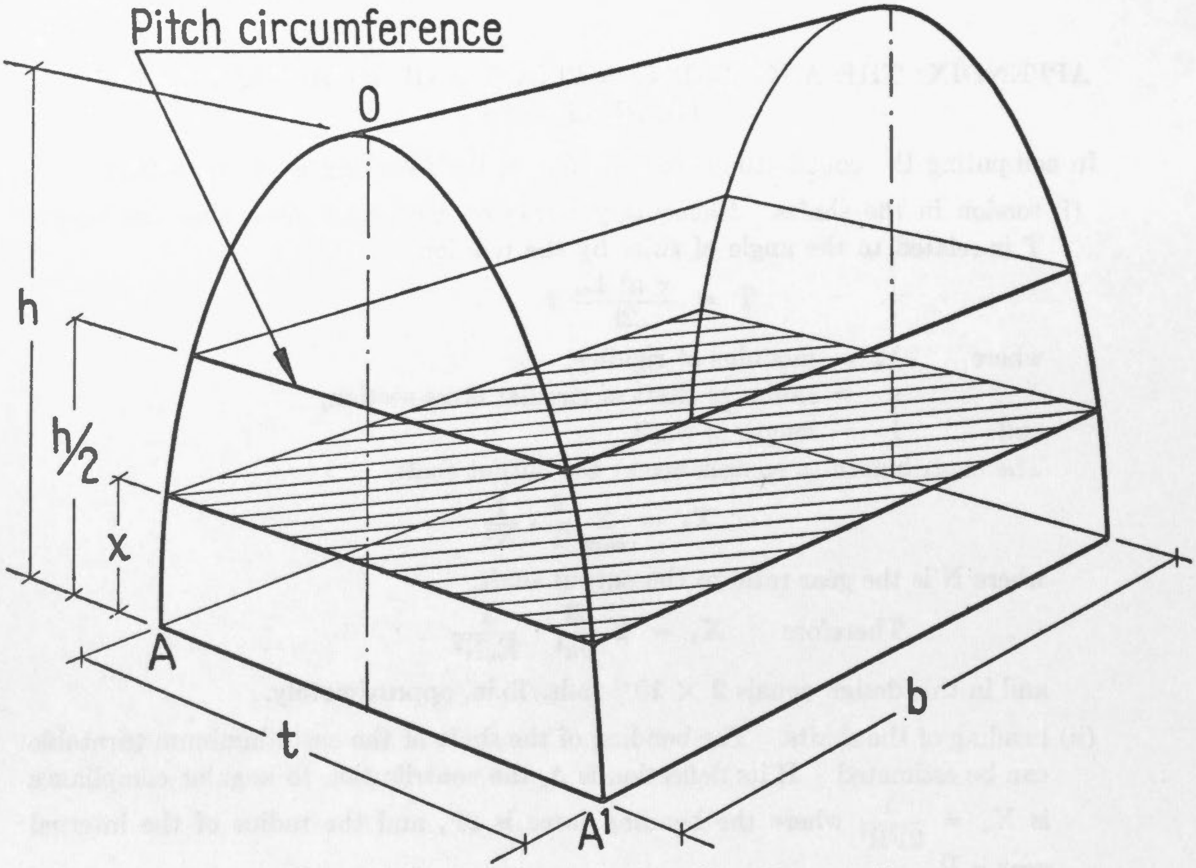

FIGURE 1.18.—Approximation to shape of involute gear teeth.

Then the external applied bending moment is $F\left(\frac{h}{2} - x\right) = EAk^2 \frac{d^2y}{dx^2}$

where E = Young's modulus, and $1 \Big/ \frac{d^2y}{dx^2}$ = radius of curvature of tooth at section where deflection is y. Integrating twice and using the conditions $\frac{dy}{dx} = 0$ when $x = 0$ and $y = 0$ when $x = 0$, we have y at the point $x = \frac{h}{2}$ gived by $y_{\frac{h}{2}} = \frac{0.6F}{Eb}\left(\frac{h}{t}\right)^3$. Other approximations lead to numerical factors similar to 0.6.

But the deflection $\Delta = y_{\frac{h}{2}}$, and if R is the radius of the gear, the torque transmitted is $T = FR$, and the angular deflection is $\theta = \Delta/R$.

The contribution to the compliance at the output shaft is therefore

$X_g = \sum_{\text{gears}} \frac{\theta}{T}\frac{1}{N^2} = \sum \frac{0.6}{Eb}\left(\frac{h}{t}\right)^3 \frac{1}{R^2N^2}$, and in this design equals 1×10^{-7} rad./lb.in. approximately.

(iv) the radial deflection of the bearings. This is difficult to estimate, but for light preloading using tight tolerance bearings it appears likely from the manufacturer's curves that $X_b = \sum_{\text{bearings}} \frac{4 \times 10^{-7}}{N^2R^2}$, or in this design about 1×10^{-7} rad./lb. in.

PART 2

THE MAGNETOMETER

2.1 INTRODUCTION

This part of the report describes the section of the airborne magnetometer which measures the intensity and direction of the magnetic field with respect to the direction reference system supplied by the gyro-stabilized platform.

The field-sensitive head of the magnetometer is mounted on the gyro-stabilized platform inside the cabin of the aircraft. It contains three mutually perpendicular magnetic detectors of the saturated transformer type, each of which is continuously maintained at the null by a direct current flowing in a solenoid surrounding it. The direct current is thus proportional to the magnetic field component along the sensitive axis of the detector. One of these units, mounted with its axis of sensitivity vertical, measures the vertical component; the others measure the fore-and-aft and the transverse horizontal components respectively.

The direct current proportional to the vertical component is measured by an automatic potentiometer. Geared to the potentiometer is a counter which indicates the vertical component in the desired units—tens of gammas.

The outputs of the two horizontal field-measuring units are combined in an electrical resolver to give the intensity of the horizontal component and the magnetic heading of the aircraft. The horizontal intensity is displayed by a counter geared to an automatic potentiometer. The magnetic heading is continuously subtracted from the gyro heading of the aircraft (supplied by the directional gyroscope), and the difference is displayed on a dial in degrees. The dial reading, when corrected for the difference between gyro-heading and the true heading, is the magnetic declination.

During normal survey flights, a switch controlling the operation of the indicators is thrown to "Average". The declination dial and the two counters, instead of following the changes in the magnetic field, now remain fixed at the last average values determined for D, H, and Z. At the end of a 5-minute period, each indicator turns automatically to a new value representing the average value of its component over the preceding 5-minute period. While the instrument is being used in this manner, three recording milliammeters record the difference between the instantaneous value of each component and the value appearing on the corresponding indicator. Thus continuous values of any component can be read from the meter records using the last determined average as a baseline.

2.2 THE MEASUREMENT OF MAGNETIC COMPONENTS

2.2.1 *The Magnetic Detectors*

The magnetic detectors are of the saturated transformer type described by V. V. Vacquier (10). The circuit in which they are used, however, is believed to represent a new technique for obtaining greater sensitivity combined with discrimination against unwanted harmonics.

The detector contains two parallel strips of Mumetal, 4.0 × 0.10 × .014 inches. Each strip is surrounded by a primary coil consisting of a single layer of No. 30 wire, close wound. The two primary coils are connected in series opposition to a source of 1000-cycle alternating current. The two Mumetal strips with their primaries are slipped into a common secondary coil of about 3300 turns of No. 36 wire. The whole unit is mounted in a bakelite tube of 0.375-inch internal diameter. The bakelite tube is threaded on the outside, at 80 threads per inch, and the solenoid which carries the direct current is wound in the grooves in a single layer.

The two units which measure the horizontal components are fixed with bakelite clamps to a horizontal bakelite plate supported by three vertical threaded rods. The vertical component measuring unit is clamped with its axis vertical to a similar bakelite plate supported by the same rods. The rods are supported by an aluminum plate carrying level bubbles which can be rotated about a vertical axis in making alignment adjustments. A transparent plastic cover encloses the magnetometer head. The magnetometer head is shown in Plate II.

The magnetometer head is thermostatted at about 30°C., although this is probably not necessary if the aircraft heating system operates normally. The temperature sensor is a thermistor which is one arm of a bridge excited at line frequency. The bridge error signal is amplified to operate a relay which applies line voltage to six carbon resistors distributed about the head assembly.

The balanced detector described above gives an output signal composed of even harmonics of the frequency of the oscillator supplying the excitation current. The amplitude is proportional to the component of the earth's field along the axis of the coils, provided this component is small, and the waveform inverts when the sign of the component is reversed. If the signal is applied to a phase-sensitive detector whose reference is double the excitation frequency, a centre-zero indication of the magnitude and sign of the component of field is obtained. However, the second harmonic content of the signal is low—of the order of 10 microvolts per gamma—and if sufficient amplication to give the required sensitivity precedes the phase-sensitive detector, the amplifier and detector are saturated by the higher harmonics of the signal. This difficulty is usually overcome by using a band-pass filter to attenuate the undesired frequencies. Any of the simpler filters with enough discrimination introduce a phase-shift which changes rapidly with frequency and with variation in the components of the filter. When a phase-sensitive detector is used, this uncertain phase-shift presents a serious problem.

It has been found possible to avoid the use of filters by tuning the magnetic detector. If the secondary coil of the Vacquier detector is tuned to the second harmonic by a condenser connected across its terminals, a great increase in sensitivity occurs as well as a relative reduction in the other harmonics. The effect is quite different from that of a tuned inductance elsewhere in the circuit—for example, infinite sensitivity and 'more than infinite' sensitivity, or instability, are easily obtained if the resistance of the secondary winding is below a critical value. The sensitivity can be reduced to a convenient value by a rheostat connected as a shunt across the secondary.

To show that this effect can be used in a practical instrument, it is necessary to investigate the variation in the sensitivity and phase of the second harmonic output of the tuned detector for small changes in the operating conditions. The non-linearity of the Mumetal cores makes analysis difficult, but it can be shown that the cores should be saturated for 28.5 per cent of the time to make the sensitivity independent of excitation amplitude. There is a value of tuning capacity for which the sensitivity is independent of frequency. If the shunting resistance is adjusted for infinite sensitivity with the optimum excitation and capacity, it can be calculated that for variations of $\pm$ 5 per cent in the excitation current, $\pm$ 5 per cent in the excitation frequency, $\pm$ 10 per cent in the tuning capacity, and $\pm$ 10 per cent in the shunt resistance, the sensitivity of the detector will remain above 1 millivolt per gamma. With the above changes in operating conditions, the variations in the phase of the detector output relative to the excitation phase are 1.2°, 0.5°, 0.5°, and 0.9° respectively. The theory of the tuned detector, from which these results were calculated, has been published elsewhere (11).

2.2.2 *The Magnetic Detector Circuits*

This section describes the circuits which excite the magnetic detectors, and produce three direct currents proportional to the three components of the magnetic field. The primary of each magnetic detector is supplied with 1000-cycle current at about 100 milliamps by a separate push-pull excitation circuit. The three excitation circuits are driven by a common Wien bridge oscillator, but each excitation circuit has its own output meter and output control.

The secondary coil of each of the magnetic detectors is connected to a tuning capacitor in parallel with a shunting rheostat, which is used as a loop gain control. The signal is amplified by a two-stage amplifier including a low-Q resonant circuit tuned to 2000 cycles. The amplified signal is detected by a phase-sensitive detector, supplied with a 2000-cycle reference signal of fixed phase by a frequency doubler common to the three channels. The D.C. output of the phase-sensitive detector is integrated by a two-stage Miller integrator, whose output is fed back to the nulling solenoid on the magnetic detector. The current passing through the solenoid is returned to ground by a manganin resistor.

Referring to Figure 2.1, the field due to the current in the solenoid is $-(A/R_s)e_3$, and the field acting on the detector is $H - (A/R_s)e_3$. Writing $R_1C_1 = T_1$ and $R_2C_2 = T_2$, and combining the three equations $T_1\dot{e}_2 = G_1e_1 - e_2$, $T_2\dot{e}_3 = e_2 - e_3/G_2$ (since $R_2 >> R_1$), and $e_1 = k(H - Ae_3/R_s)$, we obtain

$$\frac{T_1T_2R_s}{kAG_1}\ddot{e}_3 + \frac{R_s}{kAG_1}\left(T_2 + \frac{T_1}{G_2}\right)\dot{e}_3 + \left(1 + \frac{R_s}{kAG_1G_2}\right)e_3 = \frac{R_s}{A}H .$$

For $k = 200$ volts/oersted
$A = 40$ oersted/ampere.
$G_1 = 200$
$G_2 = 50$
$R_s = 200$ ohms,

the coefficient of e_3 in the differential equation is $1 + \frac{1}{400,000}$, and variation in the gain will not affect the output seriously.

If $T_1 = 0.01$ second and $T_2 = 50$ seconds, the differential equation becomes

$$\frac{1}{16,000}\ddot{e}_3 + \frac{1}{160}\dot{e}_3 + e_3 = \frac{R_s}{A}H.$$

The natural frequency of the system is $\frac{\sqrt{16,000}}{2\pi}$, or 20 cycles/second, and the damping ratio is $\frac{16,000}{160 \times 2 \sqrt{16,000}}$, or 0.4 of critical.

In practice, a small oscilloscope is connected to a check-point in the 2000-cycle amplifier and the shunt resistance across the magnetic detector is increased until the system

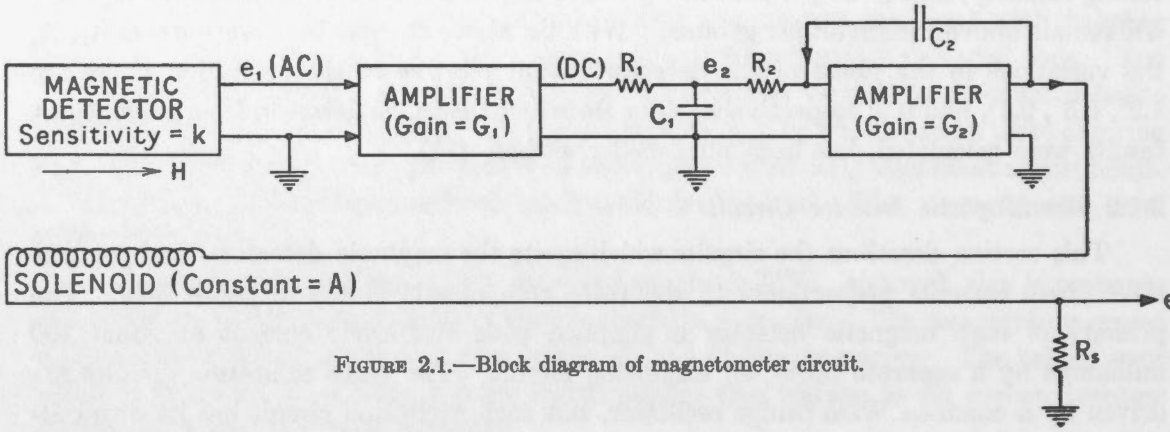

Figure 2.1.—Block diagram of magnetometer circuit.

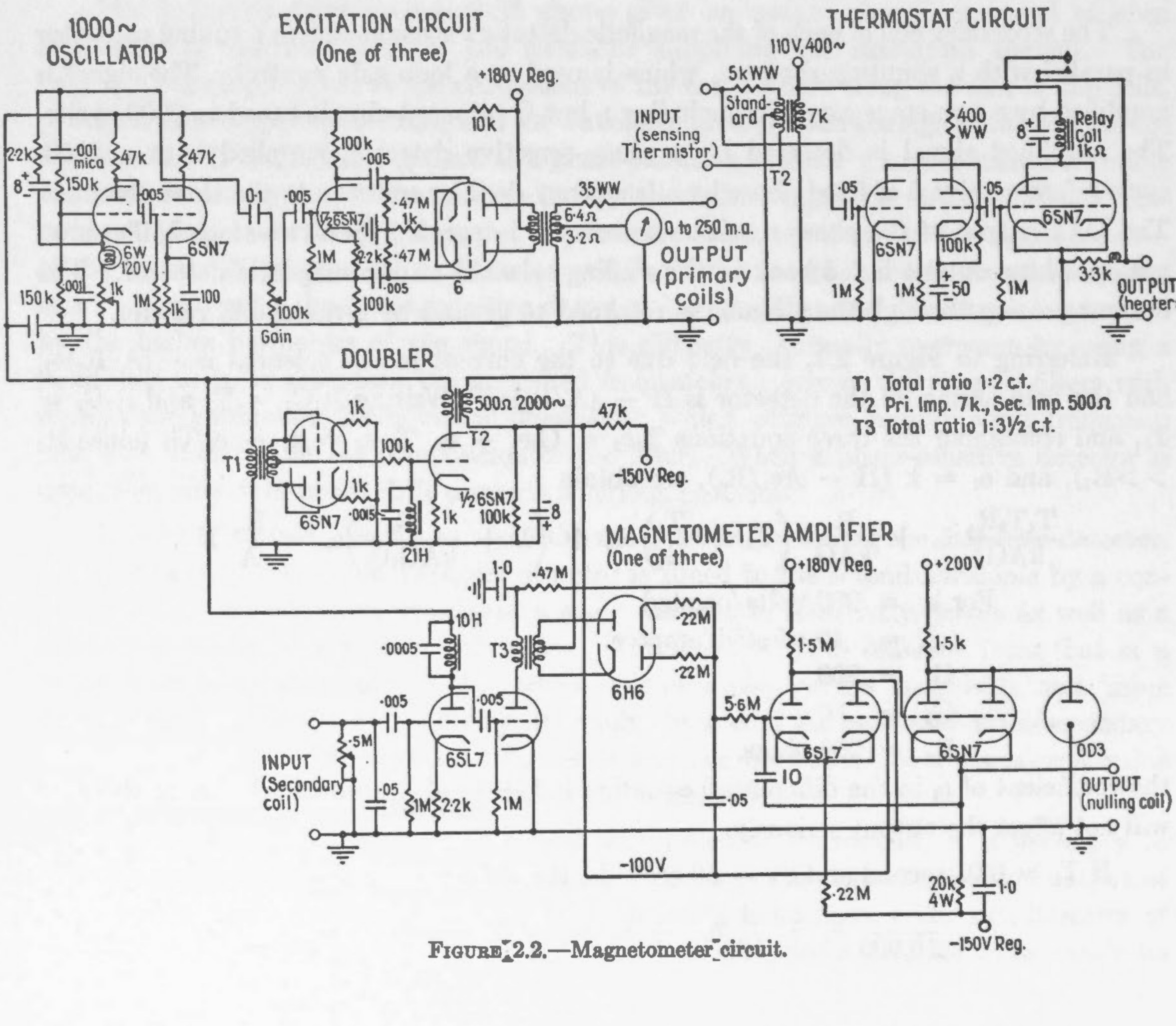

Figure 2.2.—Magnetometer circuit.

breaks into oscillation. The shunt is then reduced until the system is just stable. At any time during operation, the observer can check that the loop gain is high by increasing the shunt resistance slightly and observing the frequency of oscillation on the oscilloscope. A magnetic detector circuit is shown in Figure 2.2.

The two Mumetal strips in the detectors and their primary windings are never identical. If they are unbalanced by 1 per cent and the excitation current contains 1 per cent of second harmonic, a second harmonic signal will be induced in the secondary coil with an amplitude corresponding to about 30 gammas when the detector is in zero steady field. To avoid zero-errors of this type in measuring the components of the field, an adjustment (not shown in the figures), is provided to remove second harmonic distortion from the excitation current. The balance can be checked by throwing a reversing switch in the leads to the primary winding of the detector; if a zero-error due to harmonics in the excitation current is present, its sign is changed by the reversal, and the reading of the magnetometer will change. The setting of the adjustment usually is changed only when tubes are changed, but the adjustment can be checked at any time by throwing the switch and watching the loop error signal on the oscilloscope.

2.3 COMPUTATION AND DISPLAY

2.3.1. *Computation of Magnetic Heading and the Horizontal Component*

The direct currents passing through the solenoids of the fore-and-aft and transverse component measuring devices (with constants A_X and A_Y respectively) are returned to ground through manganin resistors R_X and R_Y, producing D.C. signal voltages (R_X/A_X) H_X and $(R_Y/A_Y)H_Y$, where H_X and H_Y are the components of the horizontal field. The two signals are combined to give a shaft angle equal to the magnetic heading of the aircraft and a signal proportional to the horizontal component of the geomagnetic field by means of an electromechanical resolver, which operates on A.C. signals.

Figure 2.3 shows the method of converting the D.C. signals to A.C., and the method of measuring the output of the resolver. A steady D.C. voltage E is applied to potentiometer P_H from a 6-volt storage battery. A steady 400-cycle A.C. voltage e is superimposed on the D.C. voltage by a transformer in series with the battery. Across the other potentiometers P_X and P_Y the voltages $k_X(E + e)$ and $k_Y(E + e)$ appear, where $k_X \approx k_Y$. The slider of potentiometer P_X is driven by a servomotor to maintain equal the two input voltages of the H_X servoamplifier, $(R_X/A_X)H_X$ and $k_XE\theta_X$. Thus $\theta_X = (R_X/k_XEA_X)\,H_X$. Then the A.C. voltage input of the H_X driver amplifier is $k_Xe\theta_X = \frac{R_X}{A_X} \cdot \frac{e}{E} \cdot H_X$. Similarly, the A.C. input to the H_Y driver amplifier is $\frac{R_Y}{A_Y} \cdot \frac{e}{E} \cdot H_Y$. The driver amplifiers are feedback amplifiers with gains of approximately one, and are designed to produce in the stator windings alternating magnetic fields accurately proportional to their input signals.

The signal induced in one of the rotor windings of the resolver controls, through the D servoamplifier, a motor geared to the resolver rotor shaft. This winding is thus maintained perpendicular to the resultant alternating magnetic field produced by the stator currents, and the A.C. voltage induced in the second rotor winding is then proportional to the resultant field. When the transformer constant of the resolver is K,

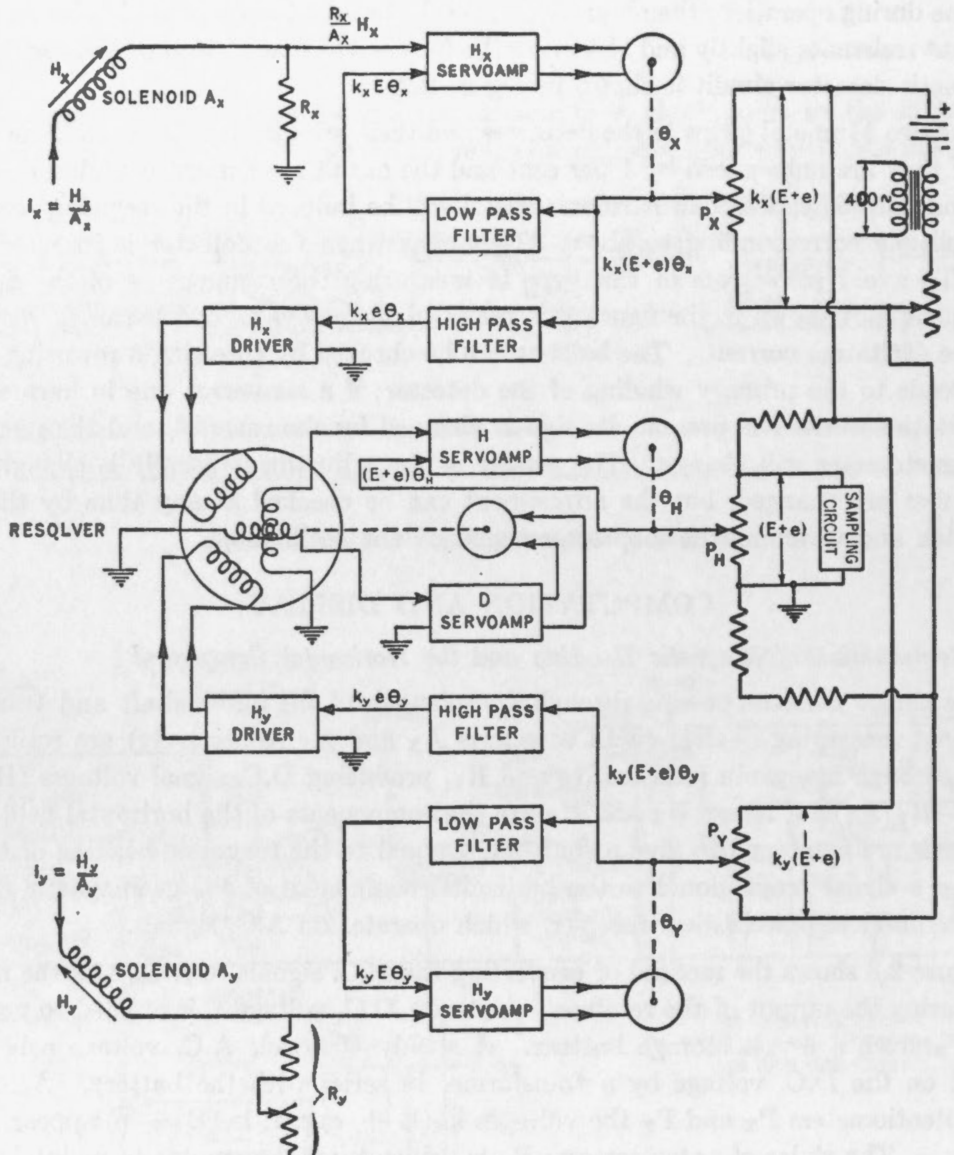

FIGURE 2.3.—D.C. measuring circuits.

the output signal is $K \frac{e}{E} \sqrt{\left(\frac{R_X}{A_X}\right)^2 H_X^2 + \left(\frac{R_Y}{A_Y}\right)^2 H_Y^2}$. If, by adjustment of R_Y, R_Y/A_Y is made equal to R_X/A_X, the output of the resolver becomes $K. \frac{e}{E} . \frac{R_X}{A_X}\sqrt{H_X^2 + H_Y^2}$, or $K \frac{e}{E} . \frac{R_X}{A_X} H$ and the shaft angle of the resolver is equal to the magnetic heading of the aircraft.

The slider of potentiometer P_H is geared to a servomotor controlled by the H servo-amplifier to keep the A.C. signal at the slider equal to the output of the resolver. Thus $e\theta_H = K \frac{e}{E} . \frac{R_X}{A_X} . H$ where H is the horizontal component of the geomagnetic field, and $\theta_H = \frac{K}{E} . \frac{R_X}{A_X} . H$. A counter geared to the shaft of P_H can be made to read the horizontal component in the desired units simply by setting the D.C. voltage E at the appropriate value.

In the construction of the instrument, it was necessary to put the potentiometers P_X and P_Y on a different chassis from potentiometer P_H. The impedance of the connecting cables introduces no error in the computation, provided it is the same for A.C. as for D.C. It will also be noticed that the potentiometers P_X and P_Y do not have to have a high degree of linearity.

The gear ratio between the shafts of the H indicator counter and the 10-turn potentiometer P_H is 48 to 1, giving a range of 0 to 48,000 gammas, where the right-hand digit on the counter represents 10 gammas. Since the linearity of the potentiometer is 0.05 per cent, the accuracy of reading is 24 gammas. Originally the range of H was limited to 0 to 20,000 gammas—sufficient for Canada—to keep the potentiometer error at 10 gammas. After the first survey it was realized that such precautions were unrealistic, and the range was increased to 0 to 48,000 gammas to cover any part of the world. The values of resistance shown in Figure 2.4 are those for the earlier range.

2.3.2. *Computation of the Vertical Component*

The circuits for the measurement and indication of the vertical component of the field are simpler than those for the horizontal component because there is no necessity for accurate conversion of signals from D.C. to A.C. The D.C. voltage produced by the current flowing through the resistor R_Z is (R_Z/A_Z) Z (Figure 2.3). It is compared with the voltage at the slider of potentiometer P_Z, and the difference is reduced to zero by the servomotor geared to the shaft of P_Z. The indicator counter, geared 80 to 1 to this shaft, is made to read in the proper units by adjusting the voltage across the potentiometer P_Z.

The range of the measuring circuit in Z is $-10,000$ to $+70,000$ gammas for the northern hemisphere, or $+10,000$ to $-70,000$ gammas for the southern hemisphere. The overlap is to avoid difficulties at the magnetic equator. The non-linearity of the potentiometer P_Z of 0.05 per cent can result in errors of 40 gammas in the reading. Originally the range was limited to the 20,000 gammas between 48,000 and 68,000.

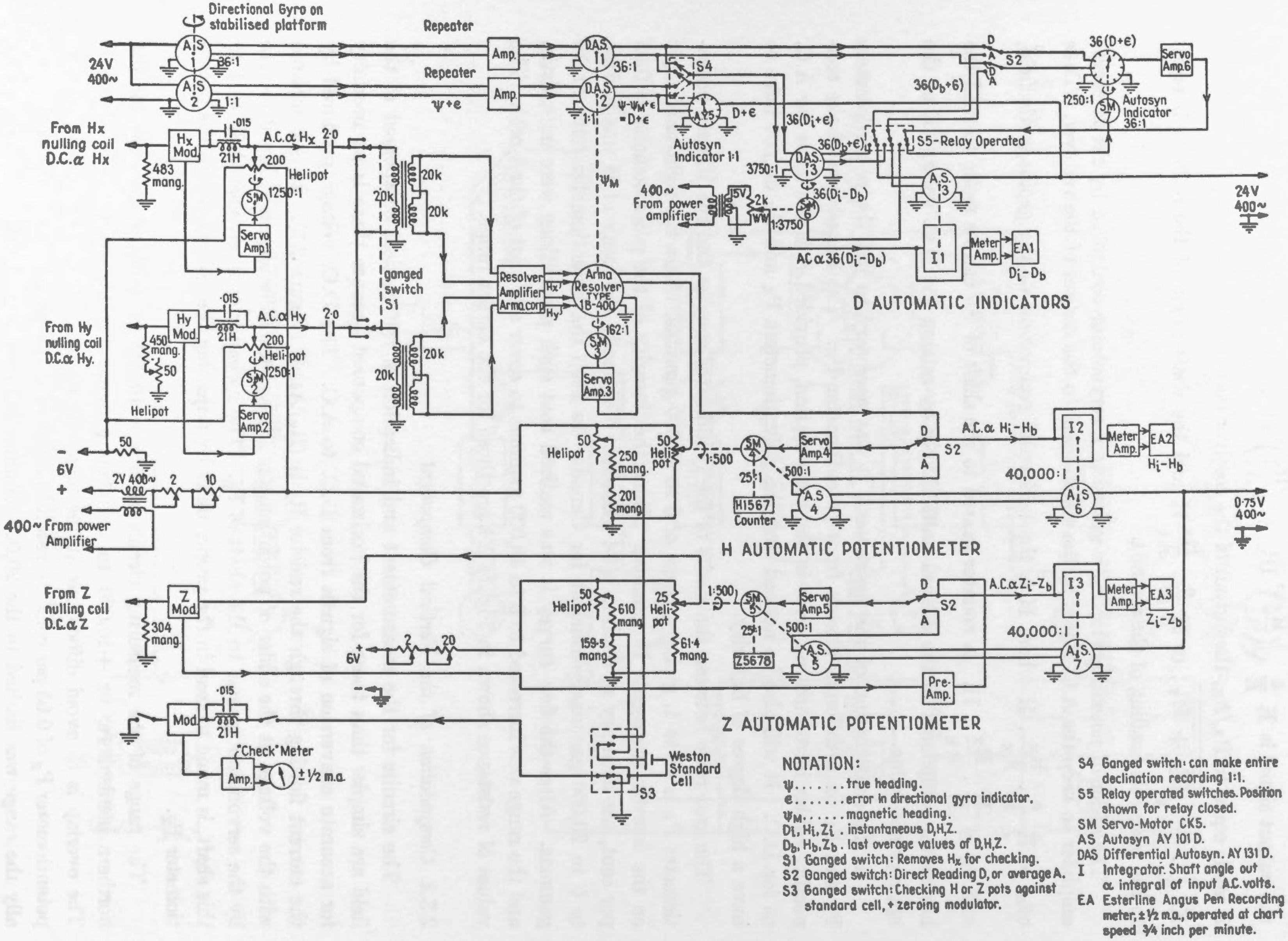

FIGURE 2.4.—Magnetometer recording system.

2.3.3 *Computation of Declination*

The vertical axis of the turntable carrying the directional gyroscope on the stabilized platform turns two autosyn transmitters, one directly and the other geared up 36 times (see Figure 1.1). The signals from these autosyns, after passing through feedback amplifiers with gains of -1 (see Figure 1.14), are applied to the stator windings of two differential autosyns geared to the shaft of the resolver, one at a 1-1 ratio, the other at 36-1. The rotor signals of the differential autosyns represent angles which are the difference between the gyro heading of the aircraft and the magnetic heading, and 36 times that angle, respectively. The 1-1 signal is applied to a self-synchronizing autosyn driving a pointer indicating from 0 to 360° on one scale of a dual indicator. The second pointer of the indicator, reading from 0 to 10°, is connected to the shaft of an autosyn receiving the 36-1 signal. The error signal induced in the rotor of this autosyn controls a servomotor geared to the autosyn shaft. (Servo operation is necessary in the case of the 36-1 pointer because of the requirements of the automatic averaging system.)

Since, generally, the directional gyroscope is not pointing north, a correction must be added to the readings of the dual indicator to obtain declination. The determination of this correction is discussed in Part 3.

Figure 2.4 shows schematically the computation of D, H, and Z. Switch S_1 is used to remove one or the other of the inputs to the resolver, to allow aligning the autosyn systems of the declination indicator.

2.3.4. *Amplifiers with D.C. Input Signals*

Three amplifiers in the magnetometer computing circuit (labelled "H_X servoamp", "H_Y servoamp" and "Z servoamp" in Figure 2.3) are required to operate servomotors on D.C. input signals of a fraction of a millivolt. The input signals are modulated at 400 cycles by vibrator-type modulators (the Brown 400-cycle converter). The resulting 400-cycle signal is amplified by an A.C. amplifier and applied to a phase-sensitive detector, whose D.C. output controls a magnetic amplifier driving the motor (Figure 2.5). Although the servomotors have heavy magnetic damping, it was found advisable to include a phase-lead network between the phase-sensitive detector and the magnetic amplifier to reduce the tendency toward instability due to the finite resolution of the potentiometers.

In order to maintain accuracy, these amplifiers must be zeroed carefully. A checking amplifier, with a vibrator modulator at the input and a centre-zero meter on the output, is included in the equipment. The checking amplifier is zeroed with its input short-circuited. It is then connected across the input of the servoamplifier to be checked while the servo is operating, and the servoamplifier is balanced to make the checking amplifier read zero. This check, which is made periodically in flight without interfering with the operation of the instrument, also insures the proper mechanical operation of the computing servomechanisms.

2.3.5. *Standardizing Circuits*

It is shown in sections 2.3.1 and 2.3.2 that the counter readings are related to the horizontal and vertical components by constants which depend on the steady D.C. voltages impressed upon the potentiometer networks. While the instrument is operating,

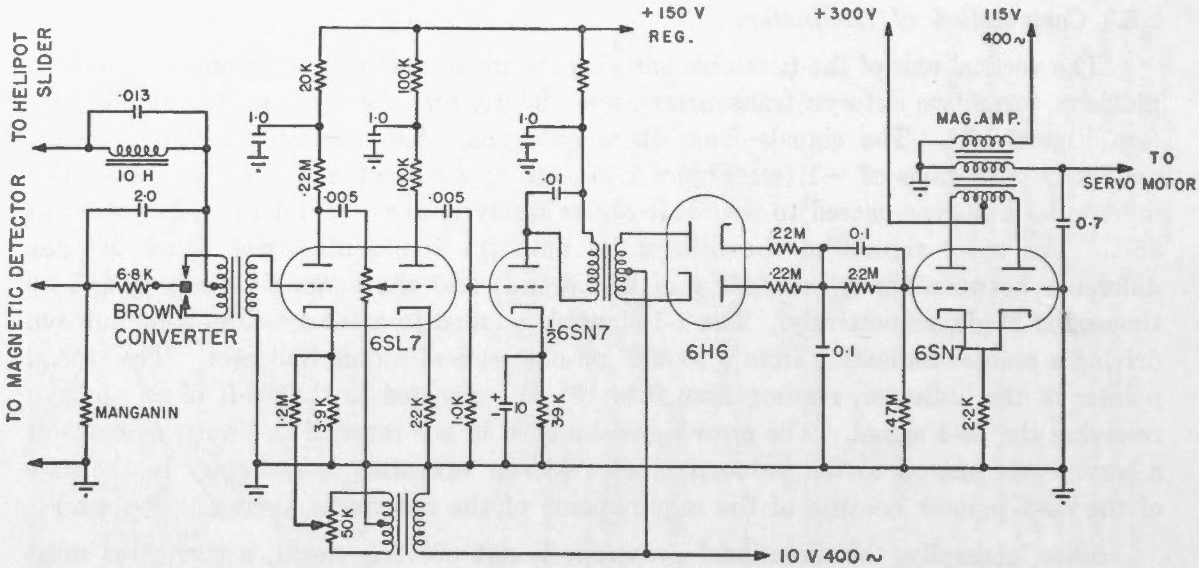

FIGURE 2.5.—Servoamplifier with D.C. input.

the two D.C. voltages must be maintained constant and at the proper value to the overall accuracy desired.

The D.C. voltages across the potentiometers P_H and P_Z (Figure 2.3) are sampled by resistive networks giving voltages of 1.018 volts when the D.C. levels are properly adjusted. The outputs of the sampling networks are compared with the e.m.f. of a standard cell, using the checking amplifier mentioned in section 2.3.4. The two sampling networks include preset helical potentiometers to allow setting the scale values in initial tests.

2.4 AUTOMATIC AVERAGING

When a switch on the magnetometer indicator panel is thrown from "Direct" to "Average", the three indicators remain fixed instead of following the changes occurring in D, H, and Z. To start the averaging process, a button is pushed, bringing into operation for 10 seconds three servo systems which align each indicator with a corresponding autosyn transmitter in the averager unit. Each of the autosyns is geared, through a 40,000 to 1 ratio, to a motor-generator unit, which is used as an integrator (Figure 2.6). The motor is controlled to make the generator output signal (which is proportional to its speed of rotation,) equal to an A.C. input signal. The input signal of each integrator is a voltage proportional to the difference between the actual value of the magnetic component in question and the value appearing on the indicator. At the end of a 5-minute period, the autosyn of an integrator will have turned through an angle proportional to the integral, with respect to time, of the input signal, and a set of relays closed by a timing circuit bring into operation the servo loop mentioned above, aligning the indicators with their integrators. A period of 10 seconds is allowed for this alignment, after which the integrating process starts again.

It will be seen that by a proper choice of integrator rate, the indicator readings can be made to represent the average of the three components of the field over the preceding

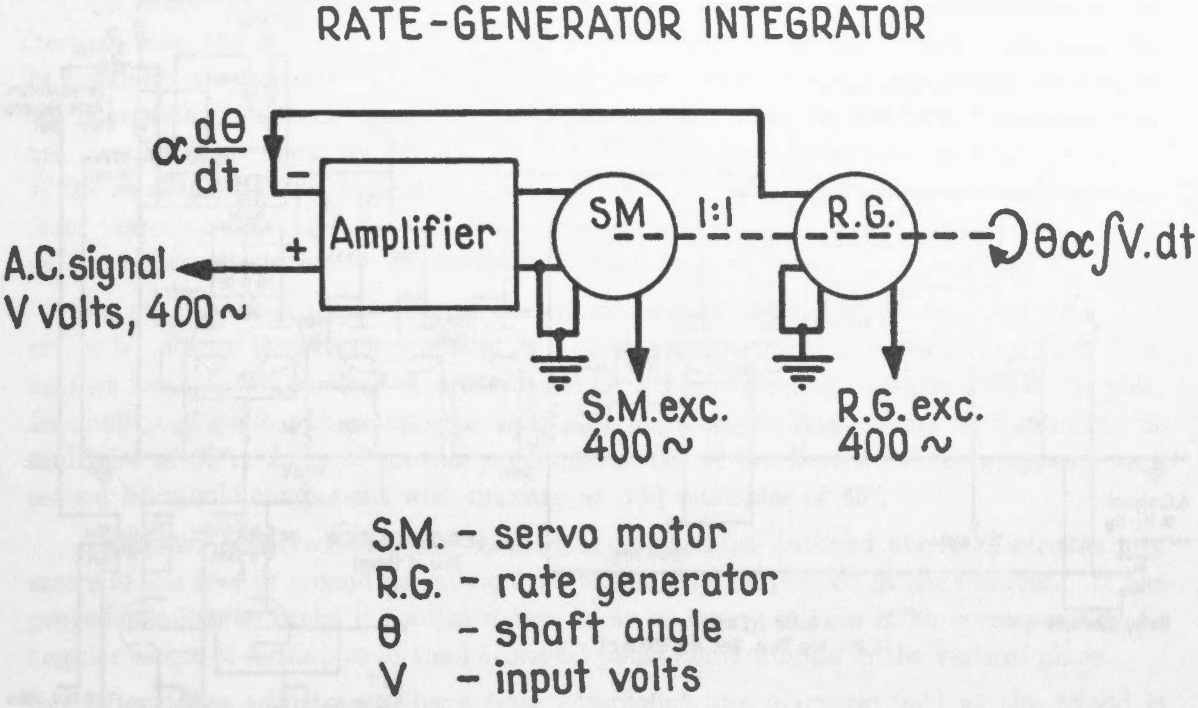

FIGURE 2.6.—Schematic of integrator in averaging circuit.

5-minute period. Since the integrators are required to accept only the range of values normally encountered during 5 minutes, the accuracy of the integration process need not be high. Errors due to incorrect integrator rate are not cumulative, and may be expected to average out over several integrating periods under normal magnetic conditions.

The gear ratios of the integrators have been chosen so that continuous gradients up to 5° in 5 minutes in D and 1600 gammas in 5 minutes in H and Z can be handled. Sharp anomalies as large as 12° in D and 4000 gammas in H and Z are handled without saturating the integrators. Close to the magnetic pole, larger gradients and anomalies may be encountered in D. Under such conditions, a switch (S_4 in Figure 2.4) is thrown to transfer the input of the averager from 36-1 system to the 1-1 system, increasing the range of the averager 36 times. The second pointer of the declination indicator is then read against the 0 to 360° scale, and the accuracy of the reading is correspondingly reduced.

In the chassis containing the automatic averager are three meter amplifiers (Figure 2.7), each consisting of a stage of A.C. amplification, a phase-sensitive detector and a cathode-follower, which are connected to three centre-zero Esterline-Angus Strip Chart Recorders. The input of each amplifier is connected in parallel with the input of the corresponding integrator. Thus the meters record continuously the difference between the instantaneous values of D, H, and Z and the values appearing on the three indicators.

The gains of the meter amplifiers are set to give full scale deflections for $\pm 2.5°$ in declination and ± 500 gammas in H and Z. Three switches are used to insert additional resistance in the meter circuits to reduce the sensitivity to one half, when large anomalies are encountered. The meters are normally operated at a chart speed of $\frac{3}{4}$ inch per minute. The chart drives are mechanically connected to maintain sychronism.

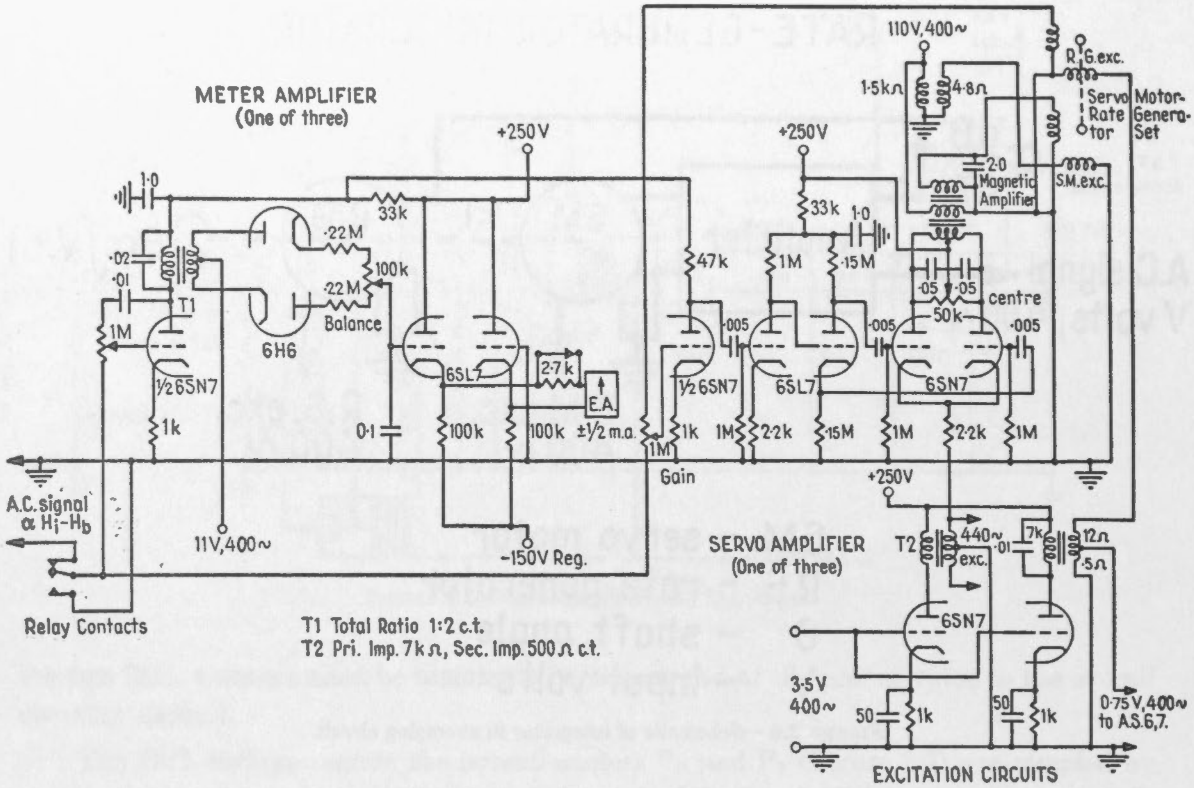

FIGURE 2.7.—Meter amplifier and averager servoamplifier.

While the indicators are being realigned with the integrators at the end of each 5-minute averaging cycle, the inputs of the meter amplifiers are grounded, allowing the amplifiers to be checked for zero-drift as well as producing time marks on the traces. When the traces are being analyzed, their sensitivities can be checked by comparing the size of the discontinuity in the trace with the change in indicator reading at the end of an averaging period. The timing of the averaging process is controlled by a clock with contacts which close for 10 seconds at the end of each 5-minute interval.

2.5 MAGNETOMETER ALIGNMENT AND ADJUSTMENT

The sensitive axes of the three field-measuring units must be mutually perpendicular and must be horizontal or vertical when the platform is level. To assist in making these adjustments, the assembly which supports the three units is mounted on a vertical axis similar to that of a theodolite. The vertical axis is attached to the stabilized platform by three levelling screws. Two level bubbles on the mounting allow this axis to be made accurately vertical in ground tests.

For alignment, the magnetometer head is removed from the stabilized platform and is levelled on a tripod away from buildings in a uniform magnetic field. Nuts on the three threaded brass rods supporting the bakelite plate carrying the vertical component measuring unit are adjusted until the Z indicator shows no change in reading as the head is rotated about the vertical axis, indicating that the axis of the Z unit is paralled to the vertical axis.

To make the axes of the horizontal component measuring units perpendicular to the vertical axis, the bakelite plate carrying them is adjusted on the vertical rods until the H indicator shows equal readings with the head oriented north and south, and equal readings with it oriented east and west. The scale values for the two horizontal coils can now be made equal by adjusting R_Y (Figure 2.3) until these four readings are equal. If the readings of the H indicator at headings NE, SE, SW, NW are compared, departure from perpendicularity of the two horizontal units is evident, and the orientation of one unit is adjusted relative to the other until these readings are equal.

In practice it is found that the simplest method of removing alignment and scale errors is to note the readings of the H indicator as the head is rotated, and plot them against heading. Levelling errors appear as a first harmonic component of the plot. Inequality of scale values appears as a second harmonic component with maxima at multiples of 90°. Lack of mutual perpendicularity of the horizontal units appears as a second harmonic component with maxima at odd multiples of 45°.

It should be noted that the method of adjustment outlined above eliminates any errors of the first or second harmonic type which may be present in the resolver. It has proved possible to make the adjustments to an accuracy of 1 in 1000, corresponding to angular errors of 4 minutes in the horizontal plane and 1 minute in the vertical plane.

After these adjustments have been completed, the magnetic field at the tripod is measured by means of a portable electronic magnetometer, of the type built by the Dominion Observatory for use in ground surveys (11). The horizontal and vertical component indicators are then calibrated by adjusting the direct currents in the two potentiometer circuits until the indicators show the proper values of the two components. The variable resistors in the voltage sampling networks are adjusted until the standardizing circuits balance against the standard cell; the settings of the variable resistors are noted and their control knobs are clamped.

Errors remaining in the magnetometer after all the alignment and calibration procedures are completed are largely absorbed in the coefficients of the magnetic field of the aircraft. The determination of these coefficients is described in Part 3 of this paper.

2.6 THE ACCURACY OF THE MAGNETOMETER

The accuracy of the magnetometer in measuring the field at the magnetometer head is now discussed, assuming that the vertical axis of the head is accurately vertical and that the true azimuth of the head is supplied to the declination indicator.

It will have been noticed that in the design of the magnetometer, null-seeking devices have been used wherever possible. This technique has the advantage—in addition to the usual factors of independence from variations in tube characteristics etc.—, that a rapid check of the nulls in the system can be made with simple built-in test equipment, without interrupting the operation of the instrument. Practically any malfunction of an element of the system, such as amplifier drift, instability or mechanical sticking of a servo, can be quickly detected and corrected by the operator.

It can therefore be assumed that the many closed-loop elements of the system operate with negligible error. The remaining sources of error are:

(a) The fact that the magnetic detectors do not always give zero signal output in zero field. The 'bias' of a given detector is not necessarily constant.

(b) The mechanical alignment of the measuring units can change because of creeping of the plastic non-magnetic parts supporting them.

(c) Changes in temperature affect the constants of the solenoids, standard cell and resistors.

(d) The resolver has inherent errors of the order of 1 part in 1000.

(e) The helical potentiometers used in the final measurement of the output have inherent errors of 1 part in 2000.

One source of zero-error in the magnetic detectors was discussed in section 2.2.2, where it was shown that errors due to harmonic distortion of the excitation current when there is an unbalance between the Mumetal cores can be eliminated. A second source is the possibility that the Mumetal cores might become permanently magnetized. Although the excitation field drives the cores well past saturation, this field decreases toward the end of the cores, and the possibility cannot be ruled out. There is evidence, however, from the use of similar magnetic detectors in portable magnetometers (11), where the magnitude of this effect can be determined in the process of aligning the instrument, that zero-errors of this sort are consistently less than 5 gammas.

It has been found that mechanical creeping occurs in the coil mountings after adjustment. By allowing a day to reach equilibrium before the final measurements are made, this effect is reduced to less than 10 gammas.

The temperature coefficient of the solenoids is of the order of 3 gammas per degree centigrade in the vertical component. Thermostating to a few degrees makes this effect negligible. The temperature coefficient of the standard cell amounts to 2.5 gammas per degree centigrade in the vertical component. In standardizing the measuring circuits corrections could be applied for the standard cell temperature, but this has not been considered justified in view of the larger uncertainties in the field of the aircraft. The temperature coefficients of the sensitive resistors are negligible.

The method of alignment of the magnetic detectors described in section 2.5 eliminates resolver error to an accuracy of 20 gammas.

The automatic potentiometers, which indicate the values of H and Z, were checked for linearity by applying a series of accurately known D.C. voltages to the circuits in place of the magnetometer signals. Measurements at 10 points showed maximum departures from linearity of ± 20 gammas; a more detailed investigation would probably show maximum errors of 30 or 40 gammas. Since the errors vary rather slowly with the position of the potentiometer slider, and the whole apparatus must be recalibrated in different regions for the effects of the magnetic field of the aircraft, it is assumed that the probable effect of potentiometer errors on survey results is of the order of 20 gammas.

It is concluded that the accuracy of the magnetometer in measuring the field at the magnetometer head with respect to the axes supplied by the direction reference system is 0.1° in declination (in southern Canada), and 20 gammas in the horizontal and vertical components.

PART 3

DISCUSSION OF SURVEY RESULTS

3.1 INTRODUCTION

The second model of the three-component airborne magnetometer which has been described in Parts 1 and 2 of this paper was completed in 1953. Through the cooperation of the R.C.A.F., it has been flown a total of approximately 400 hours during three periods of two to three weeks in 1953, 1954 and 1955. The type of aircraft used was the North Star, a four-engined airplane somewhat similar to the DC-4.

Since the aircraft was available for only short periods, it was not possible to compensate the instrument for the magnetic field of the aircraft. The aircraft field was measured by swinging the aircraft over areas where the field on the ground is accurately known. After the completion of a survey, corrections for the effect of the aircraft field are applied to the observations before they are plotted.

The techniques used in the estimation of the errors of observation and in the reduction and presentation of the results are described. The speed and ease of the reduction of the observations is a noteworthy result of the design of the instrument.

3.2 A DISCUSSION OF THE ERRORS OF THE THREE-COMPONENT AIRBORNE MAGNETOMETER

The error of an observation made in flight by an instrument of this kind may be considered as the sum of five independent errors of the following types:

(a) errors in measuring the magnetic field of the magnetometer with respect to the direction reference system.
(b) errors in the direction reference system.
(c) errors due to changes in the magnetic field of the aircraft.
(d) errors due to magnetic disturbances, and
(e) errors in geographical position.

3.2.1. *Errors in Measuring the Magnetic Field at the Magnetometer with Respect to the Direction Reference System*

Errors of this type were discussed in section 2.6. It was shown that the accuracy of the magnetometer is 20 gammas in any component of the magnetic field.

3.2.2. *Errors in the Direction Reference System*

The effect of errors in the azimuth system and in the horizontal platform on magnetic observations are now considered.

The determination of magnetic declination is illustrated in Figure 3.1, which shows the relationship between true north, magnetic north, the directional gyroscope and the aircraft heading. The instrument subtracts the magnetic heading of the aircraft β from the gyro heading of the aircraft ψ_g, and the difference $D_g = \psi_g - \beta$ is the recorded declination. This angle is independent of yawing motions of the aircraft. The electrical angle transmission system which performs the subtraction was described in section 2.3.3.

True declination is of course $D = \psi - \beta = D_g + (\psi - \psi_g)$. After the flight, the declination readings are corrected for gyro error by adding the angle $(\psi - \psi_g)$, which varies slowly because of the gyro drift.

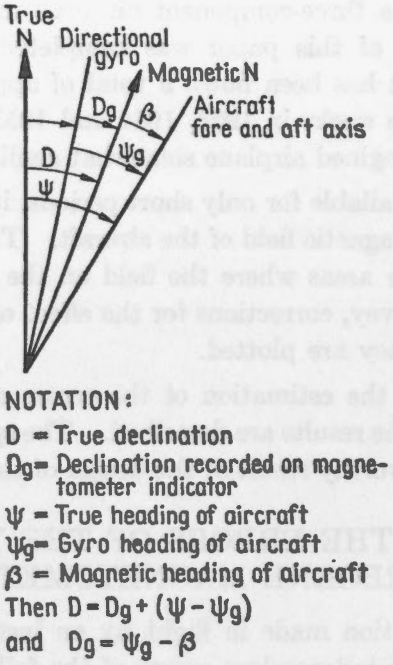

FIGURE 3.1.—Notation for angles in the horizontal plane.

In flight the angle $(\psi - \psi_g)$ is measured at 10-minute intervals by taking sets of three sights on the sun or stars with the synchronous periscopic sextant. The sextant operator holds the image of the sun on the cross-hairs by operating the altitude knob and the azimuth tangent screw. When the warning light comes on, indicating that the apparent vertical is close to the true vertical and the sextant bubble error is small, he reads the angle which appears in the field of view. This is the angle between the astronomical body and the directional gyro. The azimuth of the body is computed by interpolating in the H.O. No. 214 tables, and the angle $(\psi - \psi_g)$ calculated. This angle is the difference between the computed azimuth and the angle read in the modified sextant. The computation is usually done in flight, and a gyro plot is kept. A typical plot of the angle $(\psi - \psi_g)$ against time is shown in Figure 3.2. From the scatter of the points it would appear that the probable error of a single sight is about 0.3°, and the smooth curve is probably accurate to better than 0.2°.

The errors in D, H, and Z due to errors in the horizontal platform are now discussed. In Part 1 it was concluded that under normal survey conditions the stabilized platform is horizontal to an accuracy of 2 or 3 minutes of arc. If the platform error is p about the pitch axis and r about the roll axis, and p, r are small angles, the error in the measured magnetic heading of the aircraft β is

$$d\beta = \frac{r - p \tan \beta}{p + r \tan \beta + \dfrac{H}{Z \cos \beta}}, \text{ or}$$

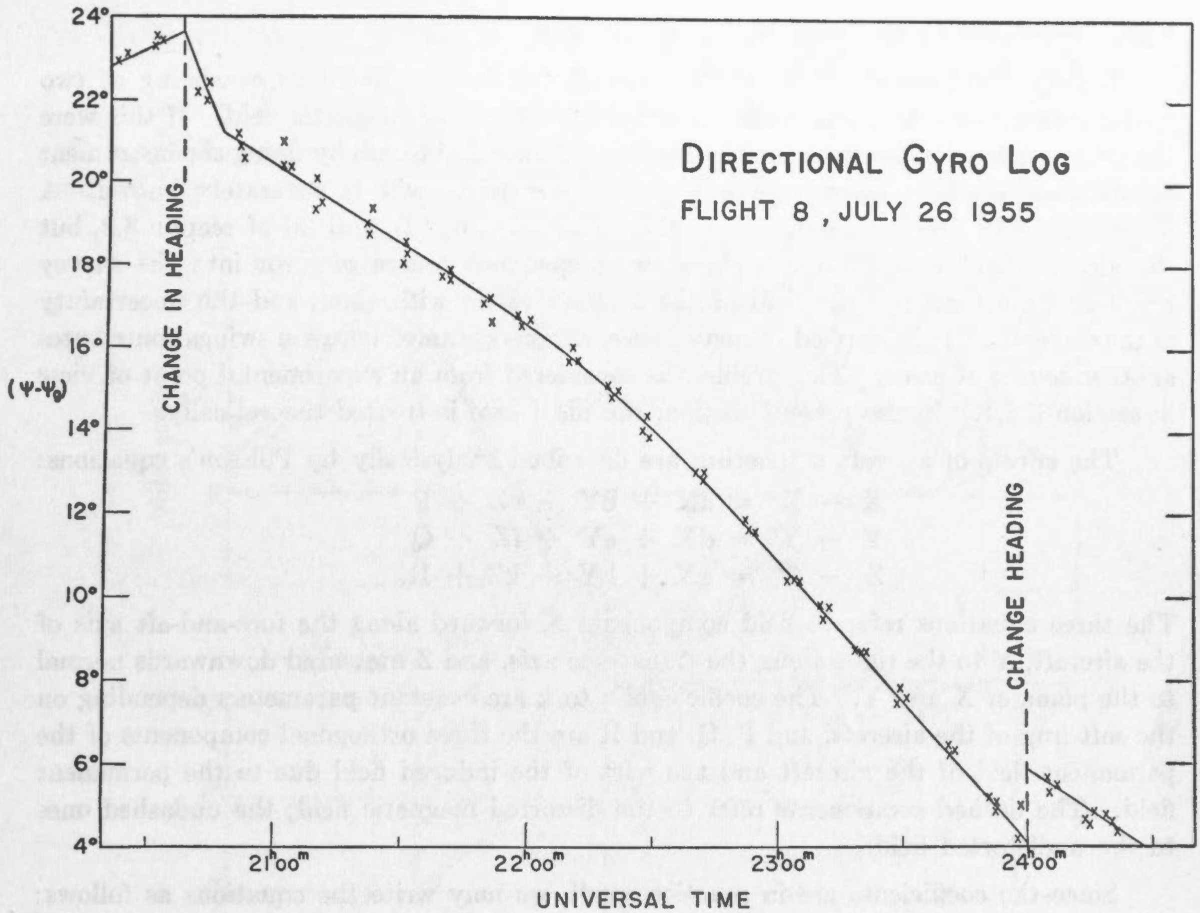

FIGURE 3.2.—Sample log of directional gyro.

$$d\beta_{(\beta=0)} = \frac{Zr}{H}, \text{ and}$$

$$d\beta_{(\beta=90^\circ)} = -\frac{Zp}{H}.$$

Errors in the stabilized platform thus produce large angular errors in declination at high magnetic latitudes, and even in southern Canada a tilt of 3 minutes produces errors of 0.2°.

The error in the horizontal field intensity is

$$dH = Z\,(p \cos \beta + r \sin \beta), \text{ or}$$
$$dH_{(\beta=0)} = Zp, \text{ and}$$
$$dH_{(\beta=90^\circ)} = Zr,$$

and in the vertical field intensity is

$$dZ = -H\,(p \cos \beta + r \sin \beta), \text{ or}$$
$$dZ_{(\beta=0)} = -Hp \text{ and}$$
$$dZ_{(\beta=90^\circ)} = -Hr.$$

In Canada, where Z is about 60,000 gammas, the maximum error in H is about 17 gammas per minute of arc of tilt, and the error in Z is correspondingly smaller. A tilt of 3 minutes can produce an error in H of 50 gammas.

3.2.3. *Corrections for the Magnetism of the Aircraft*

Ideally, the magnetic field of the aircraft can be considered as consisting of two parts: a permanent field and a field induced by the earth's magnetic field. If this were the true picture, the two fields could be measured once and for all by flying the instrument on different headings over a region where the earth's field is accurately known. A measurement of this type is subject to the errors (a), (b), (d), and (e) of section 3.2, but the aircraft field would not introduce an independent source of error into the survey results. Unfortunately, the field of the aircraft varies with time, and the uncertainty in the corrections to be applied to survey observations obtained between swings contributes another source of error. This problem is considered from an experimental point of view in section 3.5.1. In the present section, the ideal case is treated theoretically.

The effects of aircraft magnetism are described analytically by Poisson's equations:

$$\begin{aligned} X - X' &= aX + bY + cZ + P \\ Y - Y' &= dX + eY + fZ + Q \\ Z - Z' &= gX + hY + kZ + R. \end{aligned}$$

The three equations refer to field components X forward along the fore-and-aft axis of the aircraft, Y to the right along the transverse axis, and Z measured downwards normal to the plane of X and Y. The coefficients a to k are constant parameters depending on the soft iron of the aircraft, and P, Q, and R are the three orthogonal components of the permanent field of the aircraft and the part of the induced field due to the permanent field. The dashed components refer to the distorted magnetic field; the undashed ones to the undistorted field.

Since the coefficients are in practice small, we may write the equations as follows:

$$\begin{aligned} X - X' &= aX' + bY' + cZ' + P \\ Y - Y' &= dX' + eY' + fZ' + Q \\ Z - Z' &= gX' + hY' + kZ' + R \end{aligned}$$

and refer the components to the orthogonal axes defined by the true vertical and the horizontal. This approximation is valid for all normal attitudes of the aircraft.

In Canada, the vertical component of the earth's field is constant to $\pm$ 8 per cent over the whole country, and it is difficult to separate the fields induced by the vertical component from the permanent fields of the aircraft. For the same reason, it is not necessary to separate them, as long as surveys are confined to Canada. For convenience we write $cZ' + P = P'$ etc., and the equations become:

$$\begin{aligned} X - X' &= aX' + bY' + P' \\ Y - Y' &= dX' + eY' + Q' \\ Z - Z' &= gX' + hY' + R'. \end{aligned}$$

The nine parameters are determined by swinging the aircraft over a region where the earth's field is known. The methods adopted are described in section 3.5.1.

The corrections to be applied to the observed values of D, H, and Z in terms of the nine parameters are:

$$\begin{aligned} \triangle H = H - H' = {} & H'[a \cos^2\theta + e \sin^2\theta - (b + d) \sin\theta \cos\theta] \\ & + P' \cos\theta - Q' \sin\theta \end{aligned}$$

$$\triangle D = D - D' = \frac{H' [d \cos^2 \theta - b \sin^2 \theta] + P' \sin \theta + Q' \cos \theta}{H' [1 - (b + d) \sin \theta \cos \theta] + P' \cos \theta - Q' \sin \theta}$$

$$\triangle Z = Z - Z' = H'[g \cos\theta - h \sin\theta] + R',$$

where θ is the apparent magnetic heading. Figure 3.3 shows the corrections $\triangle H$, $\triangle D$ and $\triangle Z$ from the nine parameters adopted for the 1953 survey, computed for five different

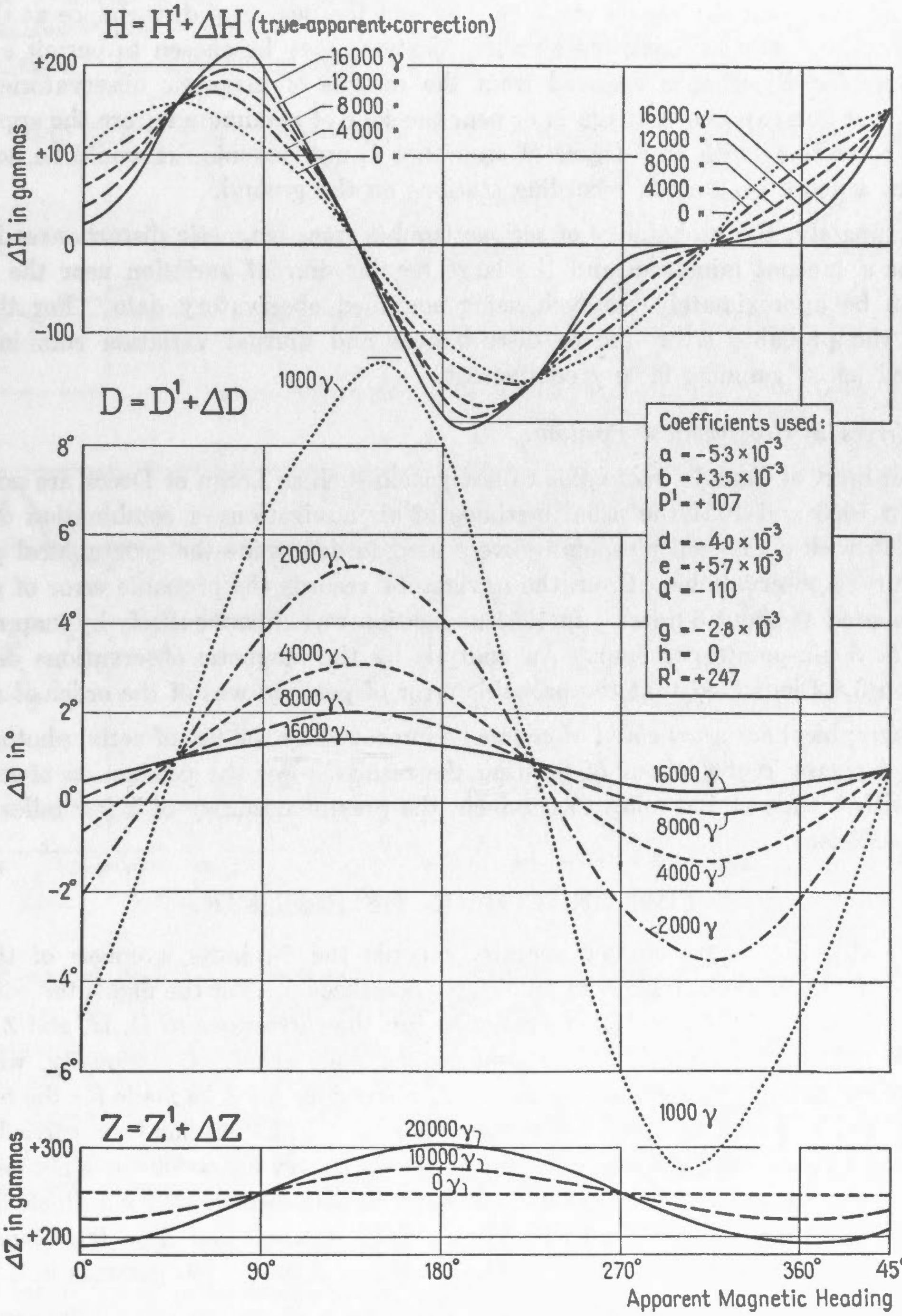

FIGURE 3.3.—Corrections adopted in 1953 for the magnetic field of the aircraft, plotted against apparent magnetic heading for different values of H'.

values of H′ and plotted against the uncorrected magnetic heading of the aircraft. In reducing the survey results, the corrections can be quickly read from these curves to an accuracy of 10 gammas.

3.2.4. *Errors due to Magnetic Disturbances*

The effect of magnetic disturbances on the airborne magnetic observations will depend on the particular region of the survey and the degree of disturbance at the time of observation. For swinging the aircraft, locations may be chosen to permit applying corrections for disturbance deduced from the records of magnetic observatories. For surveys over large areas of Canada in or near the zone of maximum aurora the application of such corrections with any degree of assurance is not possible—it would be necessary to set up a dense network of recording stations on the ground.

Fortunately, the probability of serious trouble from magnetic disturbances is fairly low near a sunspot minimum and the large regular diurnal variation near the auroral zone can be approximately removed using compiled observatory data. For the 1955 survey, the probable error due to disturbances and diurnal variation combined was estimated at 30 gammas in any component.

3.2.5. *Errors in Geographical Position.*

Over most of Canada, radio aids to navigation such as Loran or Decca are not available. In 1953 and 1954 the usual methods of air navigation—a combination of astro-navigation with occasional pin-points—were used to determine the geographical position of the survey observations. From the navigators' records the probable error of position was estimated at about 6 miles. In 1955 navigation was almost entirely by map reading, with 4 or 5 pin-points per hour. An analysis by the magnetic observations described in section 3.5.2 indicated that the probable error of position was of the order of 4 miles.

Geographical accuracy could of course be improved by the use of aerial photography, with an increase in the labour of plotting the results. For the production of magnetic charts with a scale of 100 miles to the inch, the present accuracy of a few miles is considered sufficient.

3.3 THE REDUCTION OF RESULTS

In flight, the magnetometer operator records the 5-minute averages of the field components and Universal Time on an observation sheet. After the flight, the correction to D for the drift of the directional gyroscope and the corrections to D, H, and Z for the magnetic field of the aircraft are entered on the same sheet. Occasionally, when the rate of the directional gyroscope is large, small corrections must be made for the resulting error in the horizontal platform. If the swinging of the aircraft has been carried out at the approximate altitude and magnetic latitude of the survey operations, it is not necessary to correct the observations for altitude. In any case the corrections for a dipole field are small; at an altitude of 8000 feet with $H = 15{,}000$ gammas and $Z = 60{,}000$ gammas, the correction to sea-level would be $+\ 15$ gammas in H and $+\ 60$ gammas in Z.

When the flight-lines are isolated, as in the surveys of 1953 and 1954, the results are presented as profiles. In the case of the 1955 survey, where a systematic pattern was flown, the 5-minute averages were also plotted directly on charts, ready for contouring. One man in a day can correct and plot the results from an 8-hour flight comprising nearly 100 observations of the magnetic vector, each observation representing the average of the components over a 20-mile segment of the flight path.

Figures 3.4 and 3.5 show profiles from two of the 1953 flights, drawn by joining the 5-minute averages of the components. In Figure 3.5, the dotted lines represent the instantaneous values of the field as read from the continuous recordings of the Esterline-Angus meters. The smoothing effect of the automatic averaging is apparent.

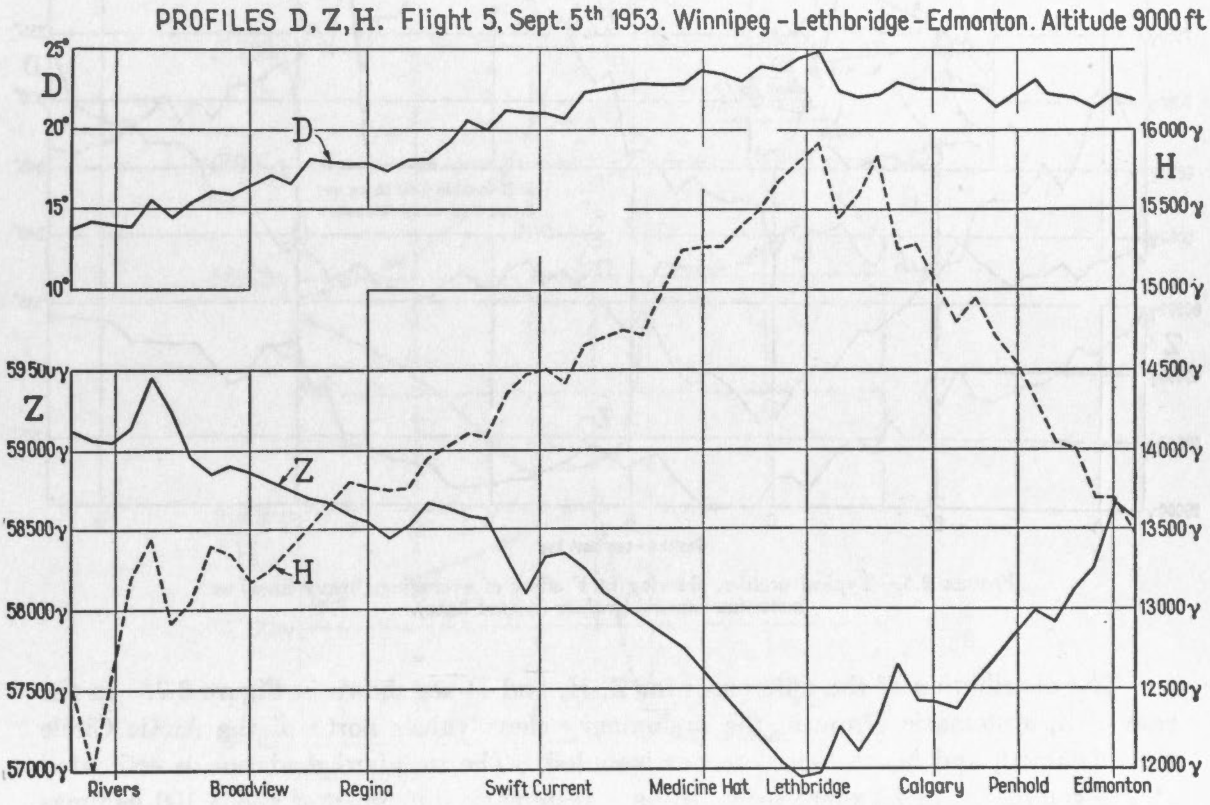

FIGURE 3.4.—Typical profiles, plotted by joining 5-minute averages.

The survey flights have been planned for the production of large scale magnetic charts rather than for the detailed study of local anomalies, but an example of a typical large anomaly in three components may be of interest (Figure 3.6). The flight path was due magnetic W across the coast line, which strikes about 50° E of N. The form of the anomaly suggests a strike in the general direction SW—NE, and the form of the Z trace suggests a fairly steeply dipping body. The agreement of the profiles shown with some theoretical examples is striking; for example, see Heiland (12).

3.4 COMPARISON OF THE 1953 RESULTS WITH EXISTING CHARTS

During the first season's operation of the instrument, a tour of Canada was made with the aim of testing the equipment in different magnetic latitudes. After the survey, the airborne results were compared with the charts for 1955.0 prepared by the Division of Geomagnetism, Dominion Observatory. In H and Z, comparisons were made at 160 equally spaced points; in D only 50 points were compared, since the complete map for 1955 was not ready. Corrections were made for the altitude of the observations and for secular change. No attempt was made to select magnetically smooth areas.

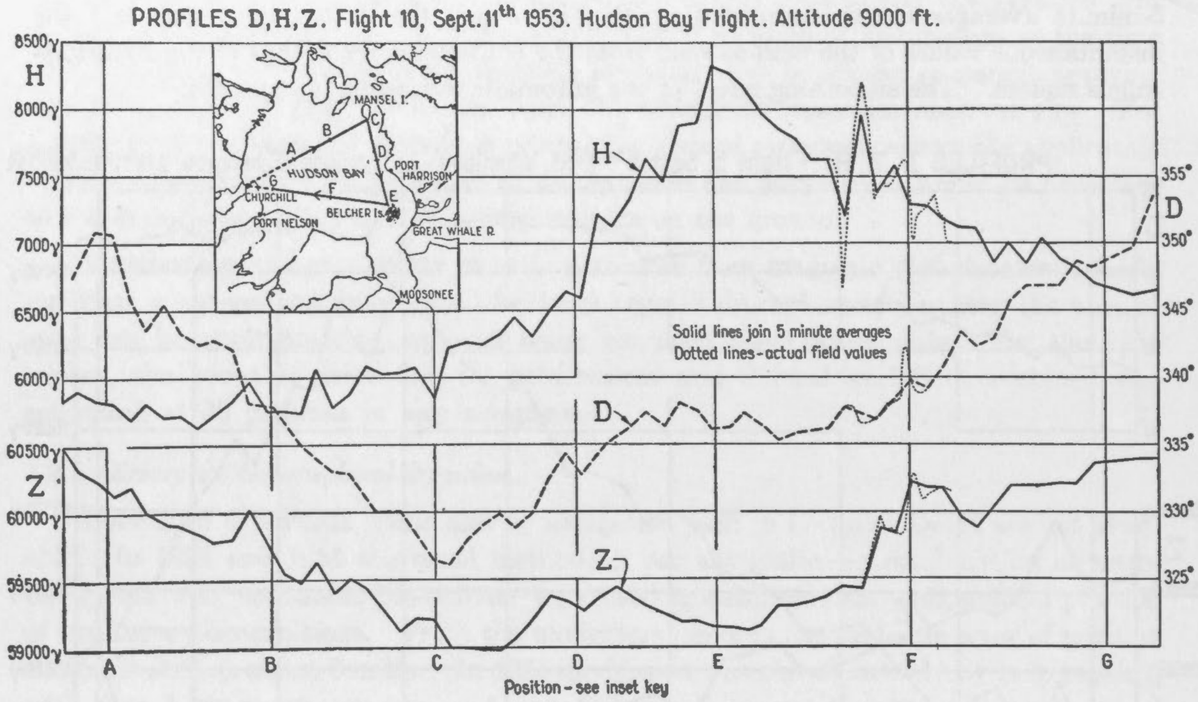

FIGURE 3.5.—Typical profiles, showing at F effect of averaging (heavy lines) on instantaneous field values (dotted lines).

The distribution of the differences for Z, H, and D are shown in Figure 3.7. In the case of Z, systematic errors in the preliminary chart values north of the Arctic Circle were detected, and hence these are not included. The standard deviation is estimated at 250 gammas. In H, there seems to be a systematic difference of about 100 gammas in all parts of Canada, with a standard deviation of 230 gammas north of latitude 60°, and 390 gammas south of latitude 60°. In the declination comparison the statistical evidence is less convincing, but the histogram is shown with its standard deviation of 1.3°.

A comparison of this sort indicates more about the degree of smoothing of the magnetic charts than it does about accuracy of the airborne observations. The standard deviations calculated above are interpreted as showing the average magnitude of local anomalies which are too small in horizontal extent to appear on large scale charts such as the magnetic map of Canada. There seem to be many anomalies in all components of the order of several hundred gammas with a width somewhere between 20 miles and a few hundred miles. A detailed analysis of the magnitude and extent of magnetic anomalies has been made from the observations of the 1955 airborne survey, and will be published elsewhere (13).

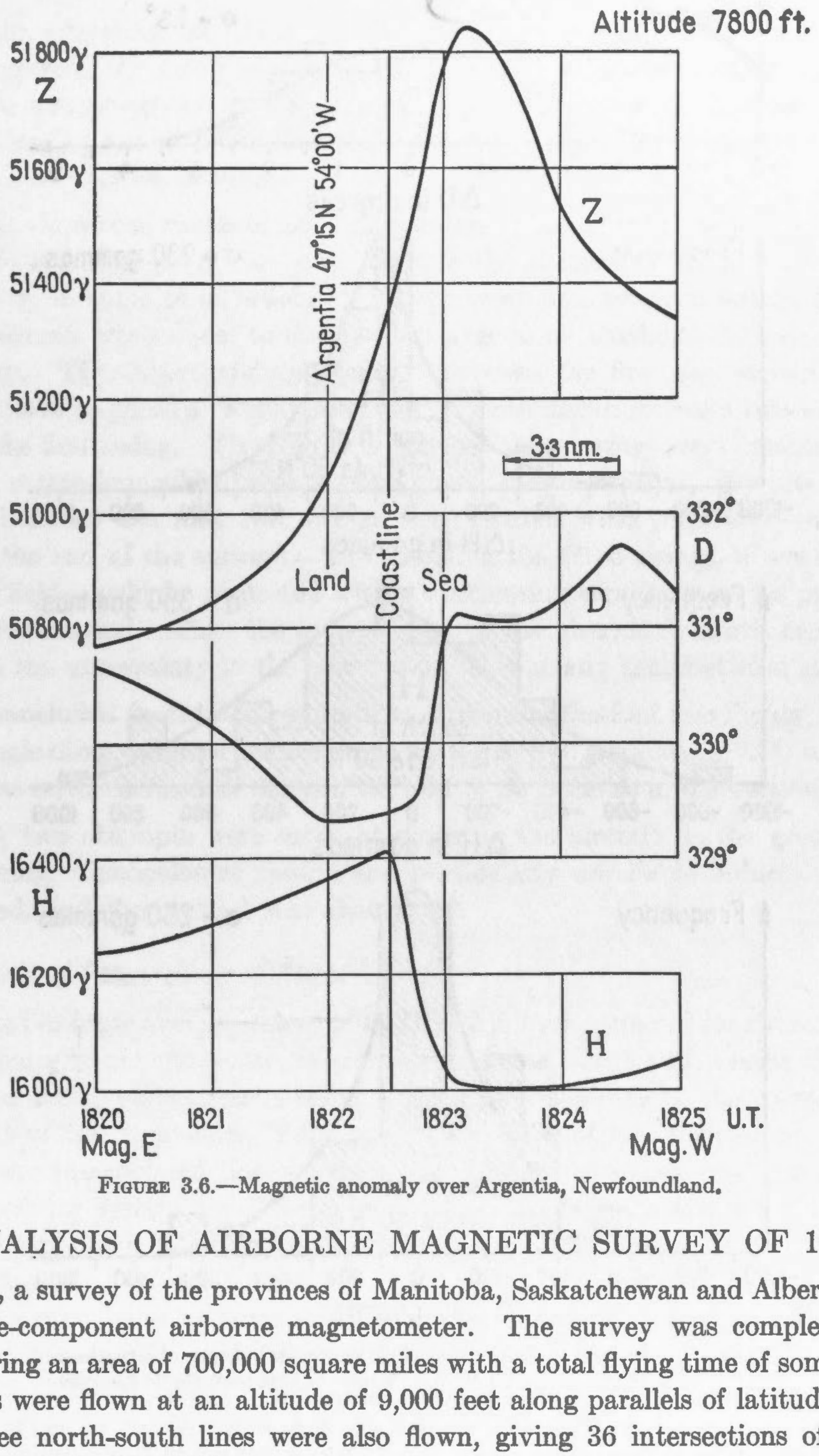

FIGURE 3.6.—Magnetic anomaly over Argentia, Newfoundland.

3.5 ANALYSIS OF AIRBORNE MAGNETIC SURVEY OF 1955

In 1955, a survey of the provinces of Manitoba, Saskatchewan and Alberta was made by the three-component airborne magnetometer. The survey was completed in three weeks, covering an area of 700,000 square miles with a total flying time of some 150 hours. Twelve lines were flown at an altitude of 9,000 feet along parallels of latitude one degree apart. Three north-south lines were also flown, giving 36 intersections of flight lines from which an indication of the over-all accuracy of the survey could be obtained. Navigation was by map-reading, with 4 or 5 pin-points per hour.

3.5.1. *Determination of the Magnetic Field of the Aircraft*

To determine the magnetic field of the aircraft four swings were made—two over Ste. Rosaire, Quebec, before and after the survey, and two over Meanook, Alberta, during

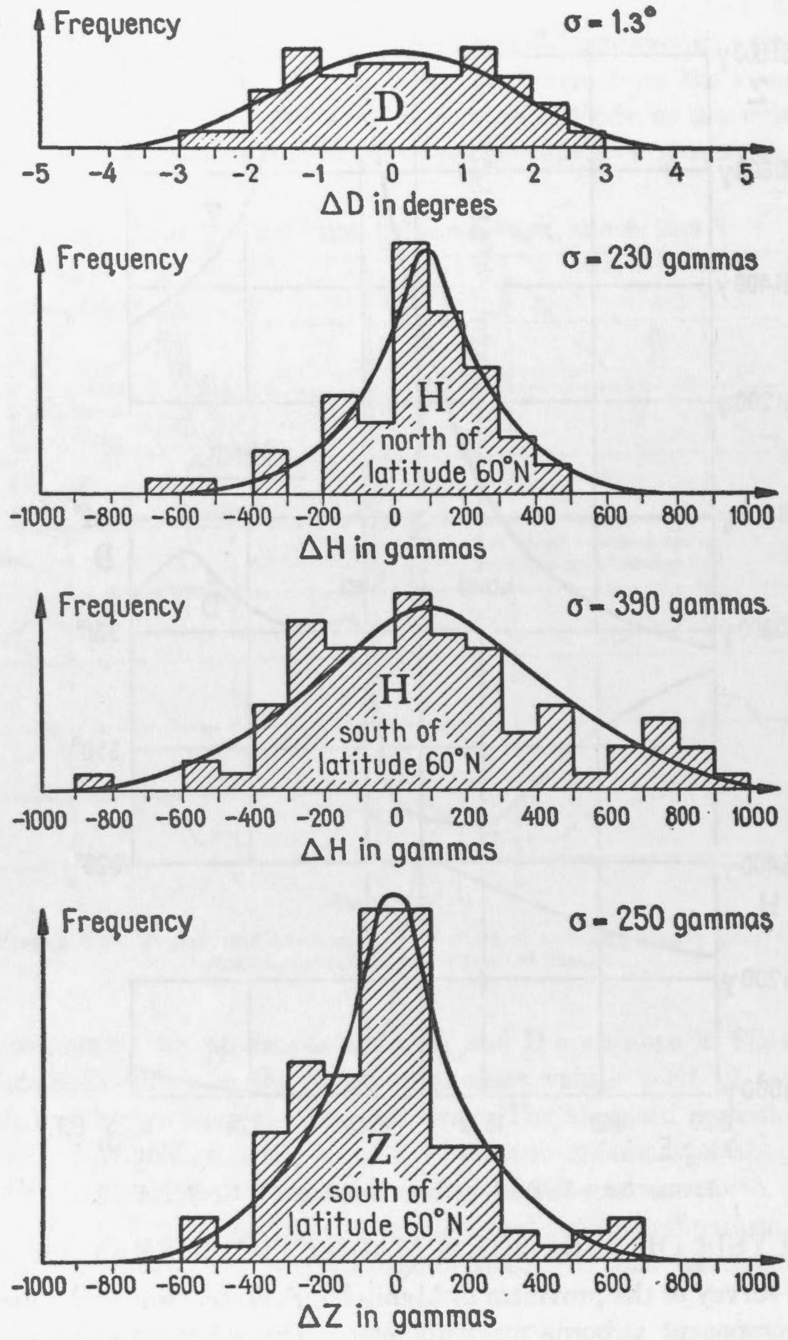

Figure 3.7.—Frequency distribution of discrepancies between observations of 1953 airborne survey and preliminary version of magnetic charts for 1955.0, based on ground observations.

the 1955 survey. The swings were made at an altitude of 9,000 feet. At both locations the magnetic field on the ground is known to a few gammas, and the gradients are less than 20 gammas per mile within 5 miles of the stations. A swing consists of eight 20-minute flights passing over the station on four different headings. This plan allows 10 minutes for the decay of transients developed in the stabilized platform during changes in heading of the aircraft. Readings of D, H, and Z are taken every half-minute with the magnetometer operating on "Direct". The readings are plotted as profiles and the differences between the airborne observations and the magnetic field on the ground as deduced from magnetograms are computed. These differences are inserted in the equations of Section 3.2.3, and the 9 parameters are obtained in a least-squares solution with the aid of a small analog computer.

Table 3.1 shows the values of the 9 parameters obtained from the four swings of 1955. The probable errors given in the table indicate the accuracy with which the equations are satisfied by a single observation. It is apparent that between swings the magnetic field of the aircraft was subject to changes too large to be attributed to errors in the individual swings. The largest change occurred between the first and second swings; the aircraft may have acquired a "semi-permanent" magnetization during a two-week overhaul just before the first swing. The results of the last three swings were combined to give a single set of corrections which were applied to all survey results. (Results obtained on two flights between the first two swings were treated with suspicion—one flight was repeated at the end of the survey). In combining the three swings, it was noticed that the induced fields could be neglected without increasing significantly the probable error of a single observation. Thus the induced part of the aircraft field was negligibly small compared to the uncertainty in the permanent fields at any time between swings.

It was concluded from these results that, excepting the first two flights, the probable error of a single observation of the magnetic vector is ± 60 gammas ($\pm 0.3°$) in declination, $\pm$ 60 gammas in the horizontal component, and $\pm$ 30 gammas in the vertical component.

In 1953, two attempts were made at swinging the aircraft on the ground with the engines running. Inconclusive results and particularly unreliable induction coefficients were obtained, and the method was abandoned.

3.5.2. *Analysis of Intersections of Flight-lines*

After the 5-minute average values of D, H, and Z were corrected for aircraft magnetism and directional gyro error and rate, they were written on charts with a scale of 1:3,000,000 (47 miles per inch), each average being written at the centre of the corresponding 20-mile segment of the flight-line. For every intersection of two flight-lines, values of D, H, and Z were interpolated linearly from the adjacent averages, and the discrepancies were examined for systematic differences which would indicate errors in the corrections for aircraft magnetism, but no statistically significant differences were found. The most probable values of the discrepancies were 1.2° in D, 140 gammas in H, and 120 gammas in Z, or more than twice as large as would be expected from the probable errors of the swing observations. (The probable difference of 1.2° in D would correspond to something less than 200 gammas, since H varies between 6,000 and 14,000 gammas in the region surveyed). This result is not surprising, since 20-mile averages on orthogonal paths would not be expected to agree unless the gradients were constant over that distance. Instantaneous readings would be expected to show better agreement than the smoothed values. Accordingly, the times of the intersections were read from the chart to the nearest half-minute, and the instantaneous values of D, H, and Z for these times were extracted from the continuous records. Although at individual intersections the discrepancies from instantaneous values differed considerably from those computed from the

TABLE 3.1

	Fore-and-aft Component				Transverse Component				Vertical Component			
	a	b	P′ γ	probable error of one observation γ	d	e	Q′ γ	probable error of one observation γ	g	h	R′ γ	probable error of one observation γ
July 18...............	−.0067	−.0044	−654	±135	−.0024	+.0200	+416	±80	−.0037	−.0038	+415	±8
July 21...............	−.0056	−.0011	−184	± 8	+.0086	−.0091	+119	±37	−.0018	+.0007	+623	± 9
Aug. 6................	−.0107	+.0057	− 80	± 70	+.0033	+.0045	+ 77	±28	−.0002	+.0029	+690	±10
Aug. 8................	+.0017	+.0021	− 32	± 8	−.0003	+.0048	+ 39	±38	−.0023	+.0025	+584	± 6
Weighted Mean *......	−.0024	+.0008	−106	± 63	+.0038	+.0006	+ 78	±58	−.0016	+.0021	+621	±33
Weighted Mean **.....	0	0	− 98	± 66	0	0	+ 75	±63	0	0	+632	±34

* Neglecting July 18. ** Neglecting induced fields and July 18.

5-minute averages, the probable values of the discrepancies were not significantly changed, as is shown in Table 3.2.

TABLE 3.2

	D°	Hγ	Zγ
Probable discrepancy at intersections			
by 5-minute averages	1.2	140	120
by instantaneous readings	1.4	140	140
Probable error of one instantaneous reading due to			
(a) change in aircraft field	0.3	70	30
(b) magnetic disturbances	0.24	22	21
(c) navigation errors of ± 4 miles	0.62	95	95
Total probable error due to (a), (b), (c)	0.73	120	100
Expected probable discrepancy at intersections	1.0	170	140

A check was made of the magnetograms of Meanook Observatory to see how much of the disagreement at the intersections could be attributed to magnetic disturbance. Although one disturbance of 200 gammas and two of 100 gammas occurred at times of intersection, the most probable disturbance (including diurnal variation) at the 72 times amounted to only 0.24° in D, 22 gammas in H, and 21 gammas in Z. No attempt was made to correct the observations for disturbances, since much of the survey lay in the zone of maximum aurora.

Next, an investigation was made of the local magnetic gradients at the points of intersection to see whether the discrepancies could be explained by reasonable errors in navigation. The maximum variations in each component which could be caused by errors of ± 1 minute in the times of intersection were read from the continuous records. The most probable values of the maximum variation in the magnetic field over 4 miles were 0.62° in D, 95 gammas in H, and 95 gammas in Z. Table 3.2 shows that the discrepancies observed at the intersections can be accounted for statistically if it is assumed that there are in fact navigational errors of the order of 4 miles. Navigational errors of this magnitude are not unreasonable when it is remembered that they include errors in plotting the flight lines and in reading the times of intersection from charts at a scale of 47 miles to the inch.

If the most important source of error is in navigation, the largest discrepancies would be expected to occur at intersections with large local gradients. The magnitudes of the discrepancies at individual intersections were plotted against the corresponding local gradients, as shown in Figure 3.8. Some correlation is apparent. A theoretically more satisfactory test can be based on the following argument. Let x be the correction to the time of intersection measured along one flight-line, and y be the correction measured

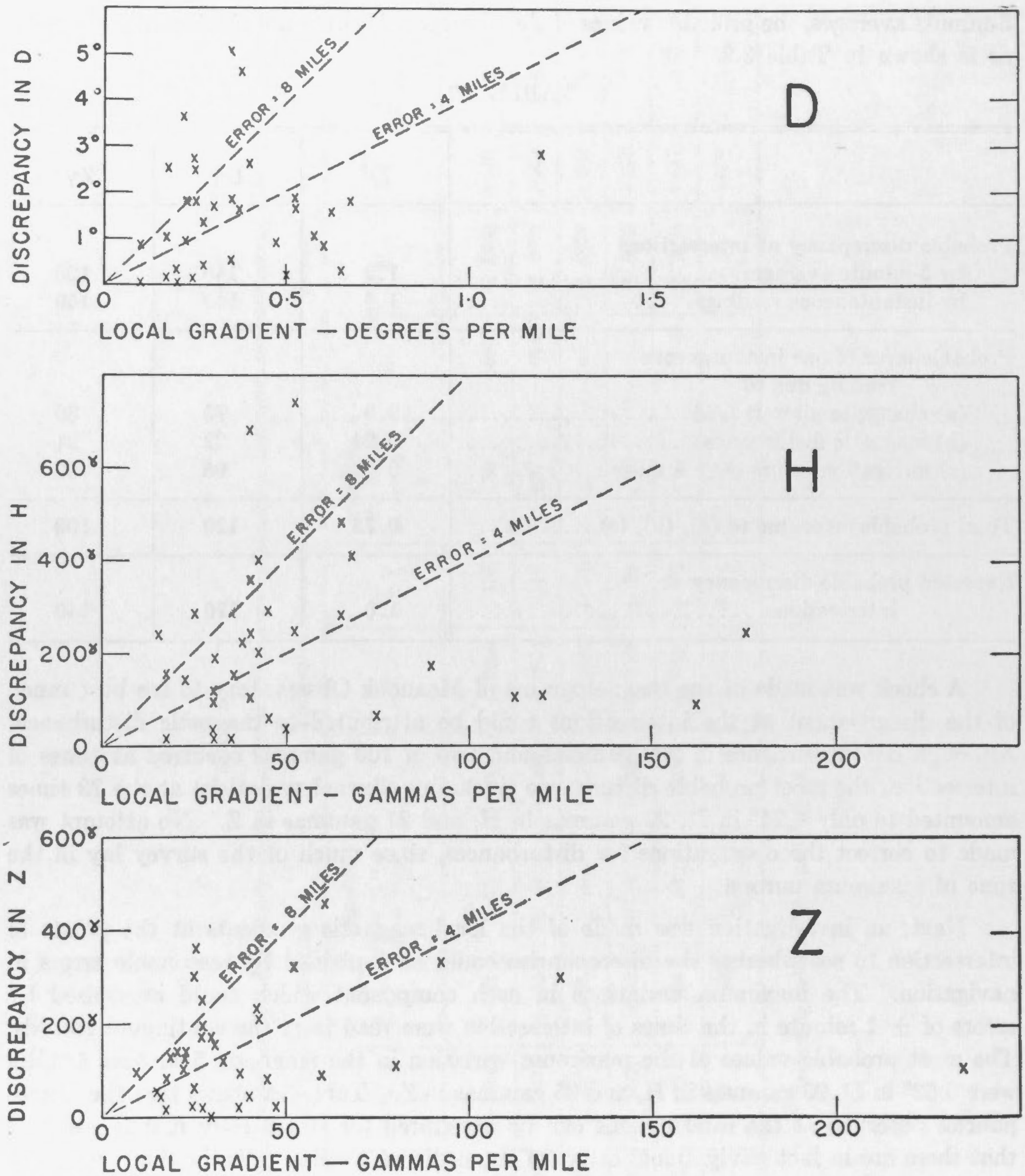

FIGURE 3.8.—Discrepancies at intersections of 1955 flight lines plotted against the local gradients.

along the other. There are generally an infinite number of pairs of corrections (x,y) for which the declination readings on the two flight-lines will agree exactly, and a line can be plotted on the x,y plane for which there is no disagreement in D. Similarly, a line can be plotted on the same diagram for H, and a third line for Z. If the discrepancies are entirely due to navigational errors, the three lines should intersect at a point, locating the flights relative to the magnetic field in a way somewhat similar to the three-star position-line method in navigation. This technique, which involves a good deal of work, was tried for four intersections. The solution for one intersection on a well-defined anomaly indicated an error of 7 miles, but the other intersections each gave several solutions within a radius of 10 miles of the assumed point of intersection any of which would make the three components agree to within 20 gammas. The method is apparently of doubtful value because the anomaly field is usually so complicated that the probability is rather large of a purely accidental coincidence, within 20 gammas, of the three position lines.

It was concluded from this analysis of intersections of flight-lines, that the probable error of an instantaneous airborne observation of the magnetic field as plotted on the charts was $\pm 1.0°$ in D, ± 100 gammas in H, and ± 100 gammas in Z. The chief source of error was the uncertainty in geographical position of the order of 4 miles, including errors in plotting the flight-lines as well as actual errors in navigation.

3.6 RELIABILITY OF THE INSTRUMENT

During the first season's operation of the magnetometer in 1953, less than 10 per cent of the flying time was lost in servicing the equipment in the air. In 1954 and 1955 unserviceability was of the order of 1 or 2 per cent. This record is considered very satisfactory in view of the complicated nature of the instrument.

The main source of trouble in the equipment has been the gyroscopes. As was explained in Part 1, the stabilized platform is designed to give the required accuracy with gyroscopes of quite modest performance by modern standards. Trimmed drift-rates of several degrees per hour would be satisfactory. It was soon found that the performance of the gyroscopes in the air bore little relation to the figures published by the manufacturers of the units. One difficulty was that the performance of the gyroscopes deteriorated rapidly owing to the formation of bubbles in the fluid by air leaking through the gyro case. Overhaul of the units by the manufacturer corrected this trouble only temporarily. Another effect, apparently not related to air bubbles, is that some units have a rate very sensitive to small accelerations, of the order of 0.02 g, when they are operated in certain positions. Non-linear relations of this type between rate and acceleration were not expected, and it was several years before laboratory tests were devised to detect them.

In survey flying, the imperfections of the roll and pitch gyroscopes do not cause as much trouble as might be anticipated. Air bubbles eventually migrate to the top of the gyro case. If the relation between rate and acceleration is fairly linear over the region of the normal aircraft accelerations, part of its effect is cancelled by adjusting empirically in the laboratory the constants of the erection system for the proper transient response. When changes in aircraft heading are made, however, as in the swinging procedure, large transient errors can be produced. On a few occasions, the platform has developed errors as large as 1° during turns of 180°. The slow decay of these errors makes the interpretation of the swings extremely difficult. In the case of the directional gyroscope, air bubbles have a more serious effect because of its horizontal attitude. Sudden changes in rate of 50° per hour have occurred in some units, making necessary frequent astronomical observations and adding to the labour of correcting the magnetic observations. The type HIG-5 gyroscopes will soon be replaced by carefully tested HIG-4 units, which it is hoped will prove more reliable.

3.7 CONCLUSIONS

Experimental results, obtained by flying on different headings over a region where the gradients of the magnetic field are small and accurate corrections for magnetic disturbances are available, show that the probable error of a single observation, after correction for the magnetic field of the aircraft, is 40 gammas in the azimuth and intensity of the horizontal magnetic vector and 10 gammas in the vertical component. This indicates that the probable error of the stabilized platform is of the order of 3 minutes of arc under conditions of frequent manoeuvering. The magnetic field of the aircraft changes over periods of a few weeks, producing an uncertainty in the corrections for the aircraft field which increases the probable error of survey observations to 60 gammas in the horizontal vector and 30 gammas in the vertical component. Errors in navigation and plotting the flight-lines and the effect of magnetic disturbances result in a further increase in the probable error of an observation, as plotted on the charts, to 100 gammas in any component.

Since the most important source of error is in navigation, the first step toward increasing the accuracy would be to reduce the navigation error by the use of aerial photography, for example. This would increase considerably the labour of plotting the observations, and where charts at a scale of 50 or 100 miles to the inch are concerned, the results would be quite indistinguishable from charts based on navigation of the present accuracy of a few miles. It is concluded that with the present techniques, the over-all accuracy of the airborne measurements is sufficient for the present purpose—the production of large-scale magnetic charts.

ACKNOWLEDGMENTS

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The history of this project is reviewed in the introduction to this paper. The initial direction of Professors E. C. Bullard and J. T. Wilson at the University of Toronto and the support and advice of the Navigation Research Panel of Defence Research Board, and its forerunner, are gratefully acknowledged. In particular, we are indebted to W/C D. A. MacLulich, R.C.A.F., who played an important part in the early development.

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Table of Russian Fault Plane Solutions

BY

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TABLE OF RUSSIAN FAULT PLANE SOLUTIONS

BY

A. E. SCHEIDEGGER

ABSTRACT

Presented here are Tables of Russian fault plane solutions as they were extracted from charts published in the Soviet Union. The notation and representation employed is the same as that used in earlier publications of this Observatory, so that western workers in the field may have access to these data.

When J. H. Hodgson joined the staff of the Dominion Observatory in 1949, he began a program to investigate the mechanics of faulting as shown by earthquakes. Making use of a method due originally to Byerly, and with the assistance of a series of student collaborators, Hodgson produced solutions for 86 earthquakes situated in various parts of the world. One of the chief results of this work was the recognition that faulting in earthquakes is, in the majority of cases, transcurrent, —a conclusion at variance with that postulated in most theories of mountain building.

In order to corroborate this conclusion, the Observatory made a survey of all available fault plane solutions (Scheidegger 1955). This summary included a restatement of the solutions obtained by Hodgson and his various coauthors, of the solutions already summarized by Honda and Masatuka, and of solutions by various other investigators. The solutions were reduced to a unified notation, and it was shown that these other solutions supported Hodgson's findings that strike-slip faulting predominated in tectonic earthquakes. The inclusion of the Japanese solutions in a summary of this sort was, in a way, special pleading, since the solutions were interpreted in terms of a fault plane mechanism rather than in terms of a focal mechanism which those authors themselves preferred.

During the same period a very active school of fault plane studies flourished in Russia under the direction of Dr. Keilis-Borok. The contribution of this school was particularly important because it kept an open mind on the question of focal mechanism. It found that a variety of such focal mechanisms do in fact exist, but that the vast majority of earthquakes are the result of simple faulting. The Russian school also developed a complete technique for the use of S and several of its derived phases.

The original intention was to make a complete evaluation of the Russian technique in English, but since the publication of a paper by Keilis-Borok (1956) in that language, this is no longer necessary. It was felt, however, that the publication of the Russian fault plane solutions in the notation employed earlier by the Observatory would be worth while, and accordingly this has been carried out in the attached tables. These solutions have never before been published in tabular form, but only on small charts with Russian explanations. The writer expresses sincere thanks to Dr. Keilis-Borok, who has drawn attention to and helped with the translation of the work done in Moscow.

Some of the solutions listed in the attached tables are slightly inconsistent in the light of the orthogonality condition, owing to the sometimes inaccurate reproduction of the charts on which these solutions had been published. Such solutions are marked with an asterisk, and the degree of inconsistency is given in a footnote. Apart from this, the notation and the make-up of the tables is identical to that in the earlier paper mentioned above (Scheidegger, 1955).

In all solutions, *a* denotes the fault plane and *b* the auxiliary plane. There is no ambiguity about this point since the Russian work is all based on S-readings.

Most of the earthquakes (viz. those in the Kazandzhik and Pamir Knot areas) listed in the attached tables are small shocks, detected by temporary field stations. The epicenters have been obtained from the published maps, and, in the Pamir Knot area, from correspondence with Dr. Keilis-Borok. The other earthquakes (in the Hindu-Kush and Japan-Bonin areas) appear to be larger shocks, and the primary data were presumably obtained from the Russian seismograph network. Their epicentres and other data are also given here as they were extracted from published Russian charts. The epicentres, in some instances, differ from those given by the United States Coast and Geodetic Survey by as much as 5°. It is considered that this is due to the way in which the Russian charts were drawn, i.e. the fault plane solutions were plotted right on the charts, which resulted in sometimes crowded conditions. This induced corresponding shifts to accommodate all the earthquakes. Also, in three cases (earthquakes of Nov. 4, 1946; May 3, 1949; July 11, 1949) there is a considerable discrepancy between the Russian fault plane solutions and those published by other workers in the field as listed in the earlier summary of fault plane work (Scheidegger 1955). The reason for this is not quite clear.

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TABLE OF RUSSIAN FAULT PLANE DETERMINATIONS

Date and Time	Epicentre	Depth (in 0.0mR)	Solution	Dip direction	Dip	Slip Angle	Fault Type	Vertical Compon.	Horiz. Compon.	Reference	
Apr 20 1941	39.2°N	0.00	a	S20°W	90°	sml	d–			V53b	
17:38:25	70.0°E		b	N70°W			s–	0.000	1.000		
Nov 2 1946	41.0°N	0.00	a	S60°W	70°	21°	–t	0.342	0.940	V53a	
18:28	76.0°E		b		70°	21°	–t	0.342	0.940		
Nov 4 1946	39.5°N	0.00	a	N62°W	74°	81°	dt	0.951	0.309	M55	* (1)
21:48	54.7°E		b	S04°E	18°	59°	st	0.276	0.961		
Feb 6 1948	20°N	0.03	a	N35°W	84°	82°	st	0.978	0.208	K54	* (2)
	146°E		b	S75°E	12°	50°	dt	0.104	0.994		
Feb 15 1948	19°N	0.03	a	N36°W	67°	86°	dt	0.920	0.391	K54	
	145°E		b	S26°E	23°	81°	st	0.391	0.920		
Mch 23 1948	50°N	0.03	a	N06°W	72°	73°	dp	0.914	0.407	K54	
	158°E		b	S52°E	24°	47°	sp	0.309	0.951		
Aug 26 1948	33°N	0.01	a	N53°W	56°	61°	st	0.719	0.695	K54	* (3)
	138°E		b	S83°E	44°	55°	dt	0.559	0.829		
Dec 15 1948	22°N	0.03	a	N01°W	87°	61°	st	0.866	0.500	K54	
	143°E		b	S76°E	30°	15°	dt	0.052	0.999		
Jan 2 1949	22°N	0.01	a	N33°W	52°	70°	dp	0.755	0.656	K54	
08:49.4	144°E		b	S65°E	41°	65°	sp	0.616	0.788		
May 3 1949	49°N	0.02	a	S44°E	74°	38°	sp	0.375	0.927	K54	* (4)
	158°E		b	N15°E	68°	34°	dp	0.276	0.961		
May 21 1949	34°N	0.00	a	S38°W	72°	66°	sp	0.883	0.470	K54	* (5)
	140°E		b	S82°E	28°	35°	dp	0.309	0.951		
Jun 5 1949	40°N	0.08	a	S02°W	68°	23°	sp	0.139	0.990	K54	* (6)
	129°E		b	N70°E	82°	31°	dp	0.375	0.927		

*Orthogonality condition not satisfied; error (1) 7°; (2) 3°; (3) 6°; (4) 21°; (5) 3°; (6) 17°.

TABLE OF RUSSIAN FAULT PLANE DETERMINATIONS—*Continued*

Date and Time	Epicentre	Depth (in 0.0nR)	Solution	Dip direction	Dip	Slip Angle	Fault Type	Vertical Compon.	Horiz. Compon.	Reference	
Jul 11 1949	34°N	0.00	a	N62°E	61°	80°	—	0.839	0.545	K54	* (7)
	134°E		b	S81°W	33°	74°	—	0.285	0.959		
Jul 14 1949	31°N	0.06	a	N14°W	76°	68°	dp	0.899	0.438	K54	
	142°E		b	S73°E	26°	34°	sp	0.242	0.973		
Sep 10 1949	39.0°N	0.00	a		54°	26°	−p	0.428	0.899	KKK53	
23:	70.7°E		b		64°	36°	−p	0.588	0.809		
Sep 15 1949	39.0°N	0.00	a		48°	67°	−p	0.682	0.731	KKK53	
22:	70.5°E		b		47°	66°	−p	0.699	0.743		
Sep 24 1949	40.0°N	0.00	a		62°	86°	−t	0.839	0.545	KKK53	
21:	70.5°E		b		33°	84°	−t	0.470	0.883		
Oct 2 1949	39.2°N	0.00	a		62°	75°	−t	0.848	0.530	KKK53	
14:	70.5°E		b		32°	64°	−t	0.470	0.883		
Oct 14 1949	39.0°N	0.00	a		35°	32°	−p	0.530	0.848	KKK53	
06:	70.6°E		b		58°	59°	−p	0.819	0.573		
Feb 23 1950	48°N	0.06	a	N05°E	56°	19°	st	0.174	0.985	K54	* (8)
	148°E		b	S69°E	80°	37°	dt	0.559	0.829		
May 25 1950	12°N	0.01	a	N54°E	72°	21°	dt	0.276	0.961	K54	* (9)
18:35:01	142°E		b	N50°W	74°	23°	st	0.309	0.951		
May 26 1950	18°N	0.03	a	N02°E	80°	82°	dp	0.970	0.242	K54	* (10)
14:33:20	145°E		b	S32°E	14°	57°	sp	0.174	0.985		
Jun 5 1950	21°N	0.04	a	S77°E	70°	26°	sp	0.309	0.951	K54	* (11)
	144°E		b	N06°W	72°	27°	dp	0.342	0.940		
Jul 13 1950	28°N	0.08	a	N69°W	35°	80°	dt	0.574	0.819	K54	
	141°E		b	S57°E	55°	83°	st	0.819	0.574		

* Orthogonality condition not satisfied; error (7) 15°; (8) 7°; (9) 8°; (10) 2°; (11) 12°

TABLE OF RUSSIAN FAULT PLANE DETERMINATIONS—*Continued*

Date and Time	Epicentre	Depth (in 0.0nR.)	Solution	Dip direction	Dip	Slip Angle	Fault Type	Vertical Compon.	Horiz. Compon.	Reference	
Oct 10 1950	36.5°N 70.6°E	0.02	a b	N45°E S38°W		lge lge	dp sp			K54	
Jan 6 1951 05:	36.6°N 70.9°E	0.05	a b	N27°W S33°W			sp dp			K54	
Jan 16 1951 08:	36.7°N 70.0°E	0.03	a b	N15°E S15°W		90° 90°	–p –p			K54	
Apr 16 1951	30°N 138°E	0.07	a b	N20°W S71°E	30° 70°	43° 67°	st dt	0.342 0.866	0.940 0.500	K54	
Jun 12 1951 22:	36.6°N 70.7°E	0.03	a b	N38°E S38°W		90° 90°	–p –p			K54	
Jul 10 1951 09:33	40°N 54°E	0.00	a b	S22°W N86°E	53° 60°.	39° 44°		0.500 0.602	0.866 0.799	M55	
Jul 11 1951	28°N 142°E	0.07	a b	N36°W S80°E	65° 36°	66° 51°	dp sp	0.809 0.423	0.588 0.906	K54	* (12)
Jul 16 1951 19:31	39°N 55°E	0.00	a b	N72°W S06°W	60° 70°	23° 32°		0.342 0.500	0.340 0.866	M55	
Aug 7 1951 09:06	40°N 55°E	0.00	a b	N11°W S64°W	50° 65°	29° 42°		0.423 0.643	0.906 0.766	M55	* (13)
Aug 10 1951	46°N 143°E	0.05	a b	N21°W N88°E	80° 61°	33° 21°	dp sp	0.485 0.174	0.875 0.985	K54	* (14)
Aug 23 1951 04:27	40°N 54°E	0.00	a b	S01°E N02°W	70° 20°	90° 89°	dp sp	0.940 0.342	0.342 0.940	M55	
Sep 5 1951 00:05	40°N 54°E	0.00	a b	N15°E S85°W	59° 60°	36° 36°	sp dp	0.500 0.515	0.866 0.857	M55	

*Orthogonality condition not satisfied; error (12) 3°; (13) 5°; (14) 11°

TABLE OF RUSSIAN FAULT PLANE DETERMINATIONS—*Continued*

Date and Time	Epicentre	Depth (in 0.0nR)	Solution	Dip direction	Dip	Slip Angle	Fault Type	Vertical Compon.	Horiz. Compon.	Reference	
Sep 7 1951 13:38	40°N 55°E	0.00	a b	S42°E S59°W	62° 70°	23° 30°		0.342 0.470	0.940 0.883	M55	
Sep 9 1951 04:03	40°N 54°E	0.00	a b	N12°E S59°E	70° 60°	35° 27°	st dt	0.500 0.342	0.866 0.940	M55	* (15)
Sep 11 1951 01:11	39°N 55°E	0.00	a b	N67°W S16°W	 90°	07°	sp dp	0.000	1.000	M55	
Sep 24 1951 00:24	40°N 54°E	0.00	a b	S39°W N37°W	80° 65°	28° 17°		0.423 0.174	0.906 0.985	M55	* (16)
Oct 4 1951 05:	36.6°N 70.6°E	0.03	a b	N06°E S31°W		lge	dp sp			K54	
Oct 13 1951 06:58	40°N 55°E	0.00	a b	N44°E S32°E	70° 60°	33° 24°	st dt	0.500 0.342	0.866 0.940	M55	
Oct 22 1951 12:04	40°N 55°E	0.00	a b	N77°E S84°W	45° 45°	85° 85°	dt st	0.707 0.707	0.707 0.707	M55	
Mch 4 1952 01:22:41	42°N 142°E	0.00	a b	N11°W S72°E	76° 28°	66° 32°		0.883 0.242	0.470 0.970	K54	
Mch 7 1952	42°N 145°E	0.01	a b	N11°E S63°E	90° 20°	71° 16°	s– d–	0.940 0.000	0.342 1.000	K54	* (17)
Mch 9 1952 17:03:43	42°N 143°E	0.00	a b	N15°W S71°E	76° 26°	69° 36°	st dt	0.899 0.242	0.438 0.970	K54	
May 28 1952 07:	37.0°N 70.9°E	0.03	a b	S59°W S57°E			sp dp			K54	
May 28 1952 07:59:09	34°N 136°E	0.05	a b	N20°E S54°E	88° 48°	44° 16°	dp sp	0.669 0.035	0.743 0.999	K54	* (18)

*Orthogonality condition not satisfied; error (15) 5°; (16) 8°; (17) 5°; (18) 11°

TABLE OF RUSSIAN FAULT PLANE DETERMINATIONS—*Continued*

Date and Time	Epicentre	Depth (in 0.0nR)	Solution	Dip direction	Dip	Slip Angle	Fault Type	Vertical Compon.	Horiz. Compon.	Reference	
Jun 2 1952 11:30	40°N 54°E	0.00	a b	N40°E S17°E	60° 55°	47° 43°	st dt	0.574 0.500	0.819 0.866	M55	* (19)
Jun 2 1952 19:	37.8°N 71.9°E	0.03	a b	S33°E N33°W		90° 90°	-p -p			K54	
Jun 3 1952 11:	36.8°N 70.6°E	0.03	a b	N47°E S47°W		90° 90°	-p -p			K54	
Jun 8 1952 18:31	39°N 55°E	0.00	a b	N13°W S39°E	35° 60°	68° 75°	st dt	0.500 0.819	0.866 0.574	M55	* (20)
Jun 25 1952 23:41	39°N 55°E	0.00	a b	N52°W S07°E	15° 80°	46° 79°	sp dp	0.174 0.966	0.985 0.259	M55	
Jul 5 1952 17:	37.0°N 71.1°E	0.03	a b	N61°E S26°W			dp sp			K54	
Jul 15 1952 22:15	39°N 55°E	0.00	a b	N60°W S05°W	25° 80°	27° 67°	sp dp	0.174 0.906	0.985 0.423	M55	
Jul 22 1952 19:58	39°N 56°E	0.00	a b	S88°W S73°E	60° 35°	79° 74°	dt st	0.819 0.500	0.574 0.866	M55	* (21)
Jul 23 1952 08:45	40°N 54°E	0.00	a b	S34°W N48°W	87° 20°	70° 08°		0.940 0.052	0.342 0.999	M55	
Aug 11 1952 14:08	38.7°N 70.5°E	0.00	a b	N00°E S56°W	22° 23°	71° 72°	dt st	0.920 0.927	0.391 0.375	KV54	
Aug 18 1952 23:16	39.0°N 70.1°E	0.00	a b	N09°W S71°E	44° 60°	41° 53°	st dt	0.500 0.719	0.866 0.695	KV54	* (22)
Aug 24 1952 17:14	39°N 55°E	0.00	a b	S07°E N42°E	55° 50°	55° 52°	sp dp	0.643 0.576	0.766 0.819	M55	

*Orthogonality condition not satisfied; error (19) 6°; (20) 6°; (21) 3°; (22) 15°

TABLE OF RUSSIAN FAULT PLANE DETERMINATIONS—*Continued*

Date and Time	Epicentre	Depth (in 0.0nR)	Solution	Dip direction	Dip	Slip Angle	Fault Type	Vertical Compon.	Horiz. Compon.	Reference	
Aug 27 1952 17:42	39.0°N 71.0°E	0.00	a b	N17°W S52°E	71° 16°	81° 57°	dp sp	0.961 0.326	0.276 0.946	KV54	* (23)
Aug 28 1952 00:50	38.9°N 70.6°E	0.00	a b	N87°W N32°E	20° 79°	33° 73°	dp sp	0.191 0.940	0.982 0.342	KV54	
Aug 31 1952 12:26	39.3°N 70.6°E	0.00	a b	N42°E S38°W	21° 62°	86° 89°	–t –t	0.470 0.934	0.883 0.358	KV54	* (24)
Sep 2 1952 18:48	40°N 56°E	0.00	a b	N86°W N21°E	50° 70°	26° 43°	st dt	0.342 0.643	0.940 0.766	M55	
Sep 3 1952 17:58	39.2°N 70.7°E	0.00	a b	S54°W N62°E	82° 08°	89° 82°	sp dp	0.990 0.139	0.139 0.990	KV54	
Sep 4 1952 11:56	39.1°N 71.1°E	0.00	a b	S05°W N44°E	60° 40°	61° 49°	dt st	0.766 0.500	0.643 0.866	KV54	* (25)
Sep 5 1952 02:36	38.8°N 70.2°E	0.00	a b	N55°W N70°E	26° 75°	39° 69°	st dt	0.259 0.899	0.966 0.438	KV54	
Sep 5 1952 13:47	38.9°N 70.4°E	0.00	a b	N47°W S46°E	40° 45°	89° 89°	–p –p	0.707 0.766	0.707 0.643	KV54	* (26)
Sep 5 1952 16:17	38.9°N 69.9°E	0.00	a b	N85°W N18°E	10° 88°	13° 80°	dp sp	0.035 0.985	0.999 0.174	KV54	* (27)
Sep 5 1952 17:14	38.8°N 70.5°E	0.00	a b	N34°W N70°E	20° 86°	14° 71°	dp sp	0.070 0.940	0.998 0.342	KV54	
Sep 6 1952 03:26	39.1°N 70.8°E	0.00	a b	N06°W S13°E	14° 77°	83° 88°	–t –t	0.225 0.970	0.974 0.242	KV54	
Sep 6 1952 11:27	39.1°N 70.7°E	0.00	a b	S81°W N03°E	70° 47°	44° 23°	dp sp	0.682 0.342	0.731 0.940	KV54	* (28)

*Orthogonality condition not satisfied; error (23) 6°; (24) 7°; (25) 3°; (26) 5°; (27) 8°; (28) 5°

TABLE OF RUSSIAN FAULT PLANE DETERMINATIONS—*Continued*

Date and Time	Epicentre	Depth (in 0.0mR)	Solution	Dip direction	Dip	Slip Angle	Fault Type	Vertical Compon.	Horiz. Compon.	Reference	
Sep 6 1952	38.9°N	0.00	a	S70°W	46°	40°	st	0.438	0.899	KV54	
15:30	70.8°E		b	N12°E	65°	52°	dt	0.695	0.719		
Sep 7 1952	39.2°N	0.00	a	N34°E	61°	61°	dp	0.766	0.643	KV54	* (29)
13:27	71.1°E		b	S75°E	40°	49°	sp	0.485	0.875		
Sep 10 1952	39.1°N	0.00	a	S15°E	60°	73°	dp	0.766	0.643	KV54	* (30)
01:43	71.1°E		b	N43°W	40°	67°	sp	0.500	0.866		
Sep 10 1952	39.1°N	0.00	a	S57°W	22°	33°	st	0.208	0.978	KV54	
19:28	70.7°E		b	N02°E	78°	71°	dt	0.937	0.375		
Sep 14 1952	39.1°N	0.00.	a	N51°W	27°	23°	dt	0.174	0.985	KV54	
21:51	71.0°E		b	N54°W	80°	65°	st	0.891	0.454		
Sep 17 1952	39.2°N	0.00	a	N29°E	74°	44°	dt	0.656	0.755	KV54	
05:03	70.5°E		b	N79°W	49°	24°	st	0.276	0.961		
Sep 19 1952	38.9°N	0.00	a	N55°E	25°	29°	st	0.259	0.966	KV54	
00:35	70.9°E		b	N60°W	75°	68°	dt	0.906	0.423		
Sep 19 1952	38.9°N	0.00	a	S20°W	85°	80°	dp	0.985	0.174	KV54	
11:01	70.4°E		b	N51°W	10°	20°	sp	0.087	0.996		
Sep 22 1952	39.1°N	0.00	a	N59°E	18°	63°	st	0.309	0.951	KV54	* (31)
02:30	71.0°E		b	S31°W	72°	82°	dt	0.951	0.309		
Sep 24 1952	39.1°N	0.00	a	S08°W	65°	77°	dt	0.891	0.454	KV54	
12:37	70.7°E		b	N38°E	27°	63°	st	0.423	0.906		
Sep 26 1952	39.2°N	0.00	a	N12°W	76°	76°	dt	0.940	0.342	KV54	* (32)
20:01	70.7°E		b	S58°W	20°	47°	st	0.242	0.970		
Sep 26 1952	38.9°N	0.00	a	N75°E	80°	79°	sp	0.956	0.292	KV54	* (33)
20:19	70.3°E		b	N64°W	17°	50°	dp	0.174	0.985		

*Orthogonality condition not satisfied; error (29) 9°; (30) 6°; (31) 2°; (32) 7°; (33) 3°

TABLE OF RUSSIAN FAULT PLANE DETERMINATIONS—*Concluded*

Date and Time	Epicentre	Depth (in 0.0nR)	Solution	Dip direction	Dip	Slip Angle	Fault Type	Vertical Compon.	Horiz. Compon.	Reference	
Sep 26 1952 21:48	39.1°N 70.5°E	0.00	a b	S18°E N02°E	14° 76°	90° 90°	sp dp	0.242 0.970	0.970 0.212	KV54	
Sep 27 1952 08:10	38.9°N 70.7°E	0.00	a b	S36°E S76°W	60° 70°	24° 33°	dp sp	0.342 0.500	0.940 0.866	KV54	* (34)
Sep 29 1952 03:44	39.0°N 70.7°E	0.00	a b	N57°W S19°E	57° 38°	68° 59°	sp dp	0.788 0.545	0.619 0.839	KV54	
Oct 3 1952 19:58	39.1°N 70.9°E	0.00	a b	N11°W S43°E	22° 70°	64° 80°	st dt	0.342 0.927	0.940 0.375	KV54	
Oct 4 1952 17:03	39.1°N 70.9°E	0.00	a b	N48°W N56°E	27° 75°	20° 64°	dp sp	0.259 0.891	0.966 0.454	KV54	* (35)
Oct 5 1952 10:40	39.2°N 70.5°E	0.00	a b	N45°E S00°E	21° 75°	46° 75°	dp sp	0.259 0.934	0.966 0.358	KV54	
Oct 6 1952 22:47	39.1°N 71.1°E	0.00	a b	S36°E N57°W	25° 70°	55° 75°	dp sp	0.342 0.906	0.940 0.423	KV54	* (36)
Oct 7 1952 19:24	39.2°N 70.7°E	0.00	a b	N60°E S20°W	28° 82°	18° 63°		0.139 0.883	0.990 0.470	KV54	* (37)

*Orthogonality condition not satisfied; error (34) 8°; (35) 7°; (36) 4°; (37) 14°

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Gravity Measurements in Quebec
(South of Latitude 52° N.)

BY

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Illustrations

Errata

Page 111, first line of Abstract, *for* "west longitude 64° W.," *read* "west of longitude 64° W.,"

Page 111, third line of Introduction, *for* "of longitude 62° W.," *read* "of longitude 64° W.,"

Page 141, 23rd line of Table, second to last column, delete plus sign.

GRAVITY MEASUREMENTS IN QUEBEC

(South of Latitude 52°N.)

By L. G. D. Thompson and G. D. Garland

ABSTRACT

The results of gravity measurements in Quebec, south of latitude 52°N. and west longitude 64°W., which have been adjusted to the common datum of the primary base network established in Canada in 1952, are presented in this report. While the data include measurements taken during the period 1945 to 1954, observations made on an air survey in 1951 cover the greater part of the area under consideration. The gravity information is presented in the form of tables of principal facts and a preliminary Bouguer anomaly map. Descriptions of primary bases in Quebec are also included.

The general anomaly pattern is discussed and an interpretation is presented. It is believed that the major anomaly trends over the Canadian Shield are caused by systematic differences in density of the Precambrian rocks. There appear to be no gravitational features along the northern boundary of the Grenville sub-province 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.

INTRODUCTION

The results for over 1700 gravity meter observations made by the Dominion Observatory from 1945 to 1954 in the province of Quebec, south of latitude 52°N. and west of longitude 62°W., are presented in this report together with an interpretation of the Bouguer anomalies in the area. The main basis of this report is a regional air survey carried out in 1951 throughout the unsettled areas of Quebec north from the Ottawa and the St. Lawrence Rivers as far as 52°N. Observations by road and rail have been included to eliminate gaps in the regional coverage and to provide more information in areas of important structures.

All of the observations have been adjusted to the common datum of the primary gravity base network established in 1952 (Innes and Thompson, 1953). The results are presented in the form of tables of principal facts and a preliminary gravity anomaly map. Descriptions of some additional gravimeter bases have been included for future reference.

In the interpretation of the gravity anomalies, particular attention is given to the significance of:

(1) the anomalies along the northern boundary of the Grenville sub-province;

(2) the local anomalies associated with the large anorthosite bodies in the area;

(3) the anomalies along the Shield boundary;

(4) the positive anomalies in the Eastern Townships and Gaspé region.

THE GRAVITY OBSERVATIONS

History of the Observations and their Adjustment

Several different gravity meters have been used for gravity measurements in this area since 1945. The extent to which each instrument has been employed and the area in which each year's observations have been made, is given in the following brief account. The manner in which the observations have been adjusted to the base network is outlined so that an estimate of the reliability of each season's observations may be formed.

1945: Observer: **A. H. Miller,**
Instrument: **Humble Gravimeter,**
No. of Stations: **137.**

Measurements with the Humble* instrument in this year constitute some of the earliest gravity meter observations made in Canada by the Dominion Observatory. While this instrument provided a great number of useful observations, it was, by modern standards, somewhat unreliable due to a high and irregular drift rate. By adjusting the Humble observations directly to the new primary bases, much of the error has been eliminated and the following traverses have been included in this report.

(*a*) A loop around the Gaspé peninsula.

This traverse was corrected to the 1952 base value at Rivère du Loup.

(*b*) Traverses north of the St. Lawrence river in the vicinity of Mont Laurier and Lake St. John.

These observations were adjusted to the 1952 bases in each area.

1946: Observer: **A. H. Miller,**
Instrument: **Atlas Gravimeter No. C-24,**
No. of Stations: **47.**

The Atlas gravimeter was used extensively by the Dominion Observatory between 1946 and 1952 for gravity work in Canada. Comparisons with more recent observations have shown that its scale constant, as supplied by the manufacturer, was adequately determined and the observations required very little adjustment to the base network. The following observations were made in Quebec in 1946.

(*a*) A traverse from Chapeau to Ottawa along the north shore of the Ottawa River.

These observations have been corrected to the base values at Pembroke and Ottawa.

(*b*) Traverses in the Eastern Townships, south of the St. Lawrence River.

These observations have been adjusted to the adopted base value at Montreal.

1947: Observer: **A. H. Miller,**
Instrument: **Atlas Gravimeter No. C-24,**
No. of Stations: **87.**

Two traverses were made in this year in Quebec.

(*a*) From Timiskaming to Noranda.

These stations have been adjusted to the primary bases at North Bay, Ontario and Rouyn, Quebec.

(*b*) From Quebec city to the New Brunswick border.

These have been adjusted relative to the bases at Quebec and Rivière du Loup.

1948: Observer: **A. H. Miller,**
Instrument: **Atlas Gravimeter No. C-24,**
No. of Stations: **66.**

*This instrument belonged to the Humble Oil and Refining Company of Houston, Texas, and was placed at the disposal of the Dominion Observatory through the courtesy of the American Geophysical Union.

Observations in this year were restricted to the Joliette-St. Michel des Saints region and have been adjusted to the network values at Joliette and Berthierville.

1948: Observer: **M. J. S. Innes,**
Instrument: **North American Gravity Meter No. 85,**
No. of Stations: **78.**

Observations were made at stations along the Canadian National railway between Quebec city, La Tuque, Noranda, and Cochrane, Ontario and have been adjusted to the 1952 base values on the route. Transportation was by means of gasoline rail speeder and regular passenger coach. High drift rates caused by uncushioned jolts of the speeder rendered the results unacceptable between Quebec city and La Tuque. However, satisfactory results were obtained from La Tuque to Cochrane.

1950: Observer: **G. D. Garland,**
Instrument: **North American Gravity Meter No. 85,**
No. of Stations: **13.**

Most of the observations made in this year north of Quebec city and in the Eastern Townships were repeated in 1952 and 1954 and the more recent values have been used. However, observations along one short traverse between Quebec city and St. Simeon are included in this work.

1951: Observer: **R. Bedford,**
Instrument: **North American Gravity Meter No. 85,**
No. of Stations: **426.**

Observations were made by road in the Noranda-Senneterre region as part of a detailed survey covering the important mining regions in Ontario and Quebec extending from Timmins through Kirkland Lake to Noranda and Val d'Or. The stations were established at 1- to 2-mile intervals to give a more detailed gravity picture. The results of this survey have been adjusted to the 1952 base value at Rouyn, Quebec and at other appropriate bases in Ontario. As it is intended to publish this survey of the mining regions separately, the principal facts are not included in this report.

A feature of this survey was the establishment of a network of stations from Rouyn to Senneterre which was adjusted to minimize the observation errors. Taschereau and Senneterre, two bases used on the air survey of the same year, were included in this network.

1951: Observer: **L. G. D. Thompson,**
Instrument: **Worden Gravity Meter No. 44,**
No. of Stations: **314.**

In 1951 air transportation was employed to establish gravity stations on the shores of lakes at about 25-mile intervals in areas inaccessible by car or rail. Nine base stations in Quebec (*see* Figure 1) were used in this survey: Taschereau, Senneterre, St. Felicien, La Tuque (Lac-à-Beauce), Waswanipi, Nemiscau, Chibougamau (Cache Lake), Oskelaneo, and O'Connell Lodge.

The adopted values for these bases and thus for all observations are relative to the 1952 base network. Taschereau and Senneterre are relative to the adopted value at Rouyn (1951 station network by Bedford). O'Connell Lodge was evaluated in 1951 by Bedford on a traverse from Senneterre to Maniwaki, the latter station being well evaluated by many direct connections to Ottawa (Saxov, 1956). Chibougamau (Cache Lake), St. Felicien, and La Tuque (Lac-à-Beauce) were established in 1952 as part of the primary base network. Nemiscau was established by air as a primary base in 1952 at the same time as Moosonee. Waswanipi and Oskelaneo were evaluated by a single air traverse from Nemiscau to Senneterre using both North American No. 85 and Worden No. 44 gravity meters.

1951-52: Observers: **L. G. D. Thompson,**
J. A. Robinson,
R. Bedford,
Instruments: **Worden Gravity Meter No. 44,**
North American Gravity Meter No. 85,
Atlas Gravimeter No. C-24,
No. of Stations: **about 125.**

During 1951 and 1952 many stations were established north of the Ottawa river in the vicinity of Lachute and south of the Ottawa river west of Vaudreuil. These observations provided data for the gravity maps included in the report on southern Ontario (Thompson and Miller, in press). The principal facts for these stations are not repeated here but the results have been considered in the preparation of the enclosed anomaly map.

1952: Observers: **R. Bedford,**
M. J. S. Innes,
J. A. Robinson,
Instrument: **North American Gravity Meter No. 85,**
No. of Stations: **40.**

The network of primary bases was established at this time.

1952: Observer: **R. Bedford,**
Instrument: **North American Gravity Meter No. 85,**
No. of Stations: **53.**

These observations were made during the establishment of the primary base network and include—

(*a*) A traverse from La Tuque to St. Roche de Mekanic along the St. Maurice river.
(*b*) A traverse from Chicoutimi to Stoneham along highway 54.
(*c*) A traverse along the Chibougamau road from St. Felicien to Chibougamau townsite.

1953: Observer: **G. D. Garland,**
Instrument: **North American Gravity Meter No. 85,**
No. of Stations: **17.**

A short traverse was made in 1953 to provide more information in the vicinity of St. Urbain. The observations were reduced relative to the base at Quebec city.

1954: Observer: **R. J. Uffen,**
Instrument: **North American Gravity Meter No. 85,**
No. of Stations: **265.**

These observations provided further control, especially south of the St. Lawrence river, and filled several gaps in the regional coverage. They include:

(*a*) A traverse of the Mont Laurier-Senneterre highway from Maniwaki to Senneterre and several roads near Buckingham.

(*b*) A traverse from St. Simeon to Baie Comeau along the north shore of the St. Lawrence river.

(*c*) A regional survey of the Eastern Townships from Huntington northward to the centre of the Gaspé peninsula.

All of this work was connected to existing bases in the 1952 network.

The Principal Facts

The principal facts for the 1952 bases and the observations prepared for this report are listed in Appendix A. They are grouped according to years and the area surveyed, starting with the 1945 results and progressing to those of 1954.

The observed gravity values have been computed to the tenth milligal.

The elevations of stations were obtained from the best information available. Most of the stations in the southern part of the region are located at railway stations, bench marks of the Geodetic Survey, or permanent marks of the Topographical Survey, for which elevations by first and second order levelling are available. In a few cases the elevations were determined by altimeter.

In the northern area covered by the air survey in 1951, elevations were determined with altimeters relative to certain known elevations. Two Wallace and Tiernan altimeters, reading to one foot, were carried in the aircraft and read before take-off and after landing at each lake. A recording microbarograph was set up at the base camp to record daily pressure variations. Since 1951, the Quebec Streams Commission has made available the results of levelling of several river systems which include the elevations of many lakes occupied on the gravity survey. Using these and every other available height control, the unknown elevations were computed by standard methods of altimetry.

The station positions were scaled from the largest scale maps available; usually 1 mile to the inch in the southern portion of the region and 8 miles to the inch in the north. Theoretical gravity at sea level was obtained from the International formula as tabulated by Swick (1942). The Bouguer anomaly was computed using a factor based on a rock density of 2.67 grams per cubic centimetre.

The Gravity Anomaly Map

A preliminary Bouguer anomaly map of the area has been prepared (*see* inside back cover), which is adequate for purposes of interpretation. While the generalized geology has been added to aid in the interpretation, for purposes of clarity only the gravity contours have been included on this relatively small scale map; the station locations and anomaly values are given in the tables. The extent of the gravity measurements in the area is indicated by the accompaning sketch map (Figure 1). Shown on this map are individual stations established during the air survey at about 25-mile intervals and traverses completed by road and rail with stations from 2 to 10 miles apart. In view of the station distribution, the contour interval has been selected as 10 milligals.

The Descriptions of Sites of Gravimeter Bases

The descriptions of several of the bases of the 1952 network in Quebec have already been published (Innes and Thompson 1953). However, the descriptions of all primary bases established in 1952 including Rupert House and the 1951 air survey bases of

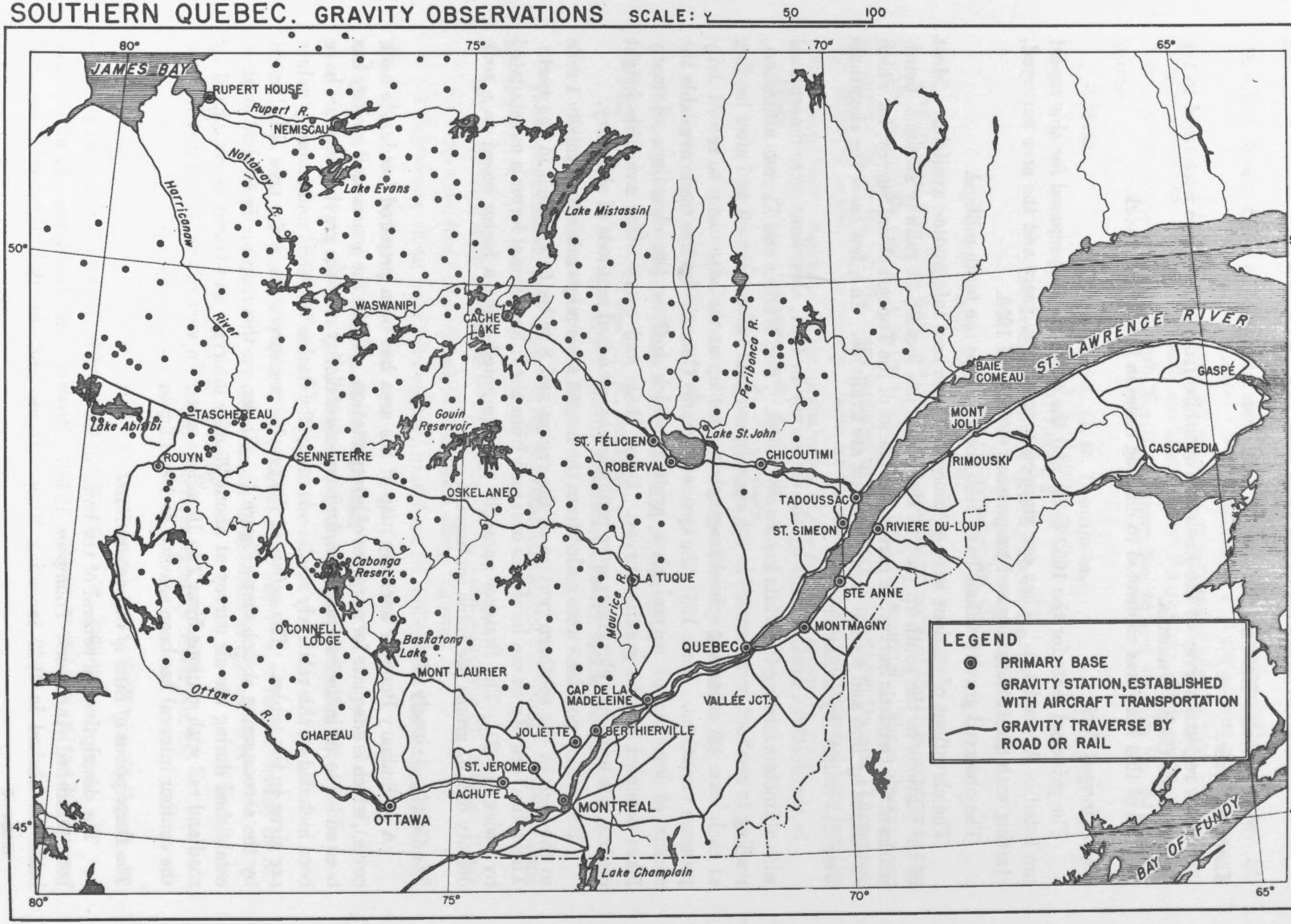

FIGURE 1.—Map of the area showing distribution of road and rail traverses and stations established by air transportation

Nemiscau, Cache Lake (Chibougamau), St. Felicien and Lac-à-Beauce (La Tuque) are presented in Appendix B of this report. Since there are only a few primary bases in the northern region which can be used for control on future surveys, it has been considered desirable to include the descriptions of the other base stations used on the air survey even though they are not primary bases.

Each diagram is oriented so that approximate north is at the top of the drawing. While the distances shown on the diagrams are exact, it should be noted that the scale, the configuration of structures and terrain are diagrammatic and intended for identification purposes only.

INTERPRETATION OF THE ANOMALIES

Extent and General Character of the Area

The area under study embraces portions of three recognized geological regions: the Canadian Shield, the St. Lawrence Lowlands and the northern Appalachians. Within the Shield the observations extend over a major portion of the Grenville sub-province and a portion of the Temiskaming sub-province to the north. In the interpretation of the gravity anomalies, attention is paid to the nature of the structures inferred within each region, and to the boundaries between regions.

While the elevation of the land surface ranges from sea level to over 4,000 feet, the greater part of the area has a mean elevation of slightly less than 1,500 feet above sea level. The highest recorded elevation is 4,160 feet, for Mt. Jacques Cartier, in the Shickshock Mountains of the Gaspé peninsula. Other regions where the elevation exceeds 3,000 feet include the Laurentian Mountains, extending along the southerly portion of the Canadian Shield, and rather limited areas of the Sutton Mountains in the Eastern Townships. Within the Shield, the general trend is a decrease in height from the Laurentian Mountains toward the north, as evidenced by the elevation of 1,401 feet at Parent, and 1,220 feet for Lake Mistassini.

Examination of the anomaly map indicates the range of Bouguer anomaly encountered. Positive values are found only within a relatively narrow strip extending, with interruptions, from the tip of Gaspé peninsula to the International Boundary near Lake Memphremagog. The highest values, as observed near Richmond, are about 45 milligals. Within the Shield itself, the Bouguer anomaly ranges between minus 10 and minus 85 milligals, the greatest negative being observed at Waswanipi in the northwesterly portion of the area. Isostatic corrections have not been computed but they are available for a few pendulum stations distributed over the area up to about latitude 49°.

Canadian Shield

The General Anomaly Pattern

Most of the area considered in this paper lies within the Canadian Shield. Since the the greater part of the gravity observations over the undeveloped regions were established on lakes at intervals of about 20 miles, it is obvious that only the major structural trends may be studied.

Very generally, the pattern of anomalies from south to north is a pronounced negative in the area immediately north of Montreal, an east-west positive trend extending from the

Ontario border to the St. Lawrence River near the mouth of the Saguenay River, a second major negative area north of this, and finally a second positive region at the northwestern limit of the area. A profile extending northwesterly from Montreal, as shown in Figure 2, crosses these chief trends.

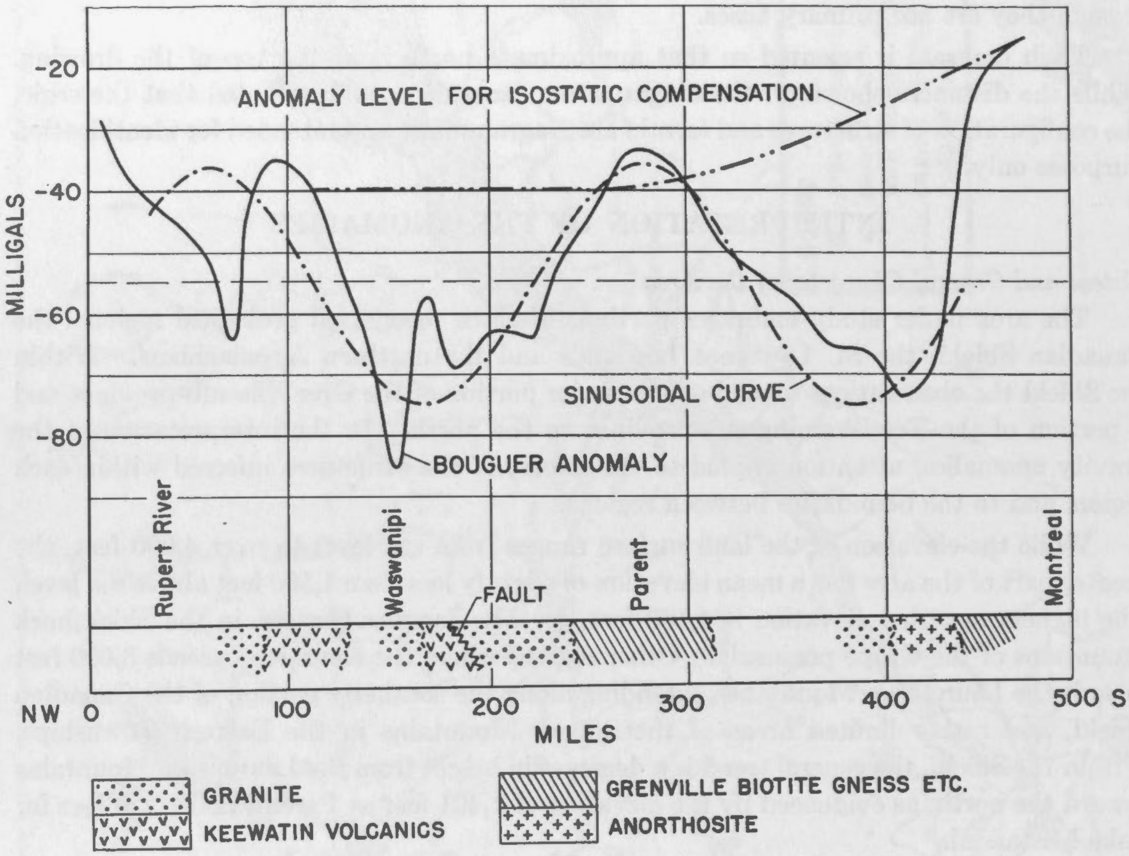

FIGURE 2.—Bouguer anomaly profile, Montreal-Waswanipi-Rupert River

In the Temiskaming sub-province of the Shield, north of the limit of the Grenville sub-province, differences between rock types are sufficiently clear cut for a correlation with the anomalies to be found without difficulty. Wherever detailed geological maps are available for comparison, as in the vicinity of Val d'Or or farther north at Broadback River (Shaw 1940), it is found that relatively high Bouguer anomalies occur over the dense Keewatin volcanics, while much more negative values extend over granitic rocks. Within the Grenville region, however, the problem is more difficult partly because much of the area is not mapped in detail, and also because of the gneissic, foliated character of the rocks which makes the boundaries between rock types often indistinct and makes the representative sampling for density determinations very difficult. Following early gravity surveys over extensive Precambrian areas, the existence of considerable variations in anomaly level over broad regions mapped simply as "gneiss" or "granite" appeared to imply a hidden cause for the effects. Consequently, the broadest trends of this type were ascribed to warpings of the crustal layers, rather than to density variations in the surface rocks (Garland 1950). However, more detailed studies of specific areas (Oldham 1954) have shown that there are in fact systematic differences between the densities of various types of the gneissic rocks, and that major distortions of the anomaly field may be produced by these density variations. In the Parry Sound region of Ontario, Oldham showed that within an area about 20 miles in diameter, the dominant rock type was biotite and hornblende gneiss with a mean density of 2.85 gms/cc., and that this area was surrounded by more granitic gneisses of mean density 2.69 gms/cc. If this difference in density extends in depth for some thousands of feet, it could explain the observed variations in Bouguer anomaly.

It remains to demonstrate the degree of correlation between the major anomaly trends and the rock types for the Grenville region in Quebec. Along the extreme southern edge of the exposed Shield, from the vicinity of Ottawa to the lower St. Lawrence, the anomaly is relatively high, that is, above minus 30 milligals. This area includes the Grenville type area of Logan (1847), and the Buckingham and other areas studied in detail by Wilson (1920, 1924, 1925). The dominant rock types in these areas appear to be metamorphosed sediments, such as crystalline limestone and sillimanite-garnet gneisses. It is true that these are intruded in many areas by granite, but on the whole the denser, metamorphic types predominate. The region includes also numerous basic intrusives, termed the Buckingham series by Wilson, and the local effect of these on the gravity map may be seen in the type area, north of the town of Buckingham. The densities of the intrusive rocks are found to be over 2.85 gms/cc., and of the surrounding gneiss, 2.83 gms/cc.

There is in addition an intense local anomaly, reaching values of plus 20 milligals over a breadth of 10 or 12 miles, in the vicinity of Huntingdon, southwest of Montreal. The Precambrian rocks in this vicinity, north of the International Boundary, are everywhere concealed by Cambrian and Ordovician strata of thickness between 500 and 1,700 feet (Dresser and Denis, 1944, p.255). However, the positive anomaly is on strike with a belt of gabbro known in the Malone district of New York (Buddington 1939), and it would appear that what is observed is the effect of the northeasterly extremity of this belt.

The boundary between this southerly area of higher anomaly and the more negative area to the north follows a smooth arc from near Mont Laurier to the St. Maurice River, then runs northerly for some miles. The contour map and the profile in Figure 2 demonstrate the sharpness with which the anomaly decreases. Included in the negative area north of this rapid decrease is the mass of the Morin anorthosite, which is discussed in more detail later, and the associated acid intrusives, such as syenite, described by Osborne (1938). Furthermore, Osborne (1936) has shown that in the vicinity of Shawinigan Falls, where the anomaly contours run almost north-south, there is a transition in rock types from granitic gneiss on the west to basic gneisses and amphibolite on the east. Much of the area which underlies this broad negative belt is unmapped in detail, but it seems reasonable to presume that the dominant rock type is granitic gneiss or acidic intrusions.

Proceeding northward, we observe the next major feature of the map to be a belt of relatively high anomaly, with a remarkable east-west trend from near the boundary of the Grenville sub-province, through Parent, to a broader high area north of Quebec city. Near its western end, this belt includes the Cawatose area mapped in detail by Wahl and Osborne (1950), in which the dominant rock is described as a biotite paragneiss. Analyses given by these authors show that this rock consists principally of plagioclase, quartz, and biotite, with an average volume content of 25 per cent of the latter mineral. Such a rock would have a theoretical mineral density of 2.77 gms./cc. By contrast, a "pink granite gneiss" found in minor amounts in the same area is given as being composed of plagioclase, microcline, quartz and an average of 5 per cent of biotite. The theoretical mineral density of this rock would be 2.63 gms./cc.

In the area north of Monet, on the Canadian National railway line west of Parent, the rock types along the belt of higher gravity are also known in some detail. The mapping of Faesaler (1936) indicates a gradation from biotite paragneiss, in the vicinity of the railroad, to granitic rocks near the northern limit of his map-area, which lies about 50 miles to the north. As shown in Figure 2, this gradation corresponds to the decrease in anomaly from minus 30 to minus 70 milligals.

The negative belt north of this gradient extends in an east-west direction across the north of Lake St. John, from at least as far west as the boundary of the Grenville, to the eastern limit of the area covered by the gravity observations. It includes the large anorthosite mass north and east of Lake St. John, the Roberval granite described by Dresser (1916), and large areas of granitic rocks mapped by the Quebec Department of Mines (Map No. 961, 1952). Apart from the anorthosite, the rocks appear to be dominantly granitic. They are bordered on the north, in part, by basic volcanics of Keewatin type, as in the Surprise Lake area (Deland 1953), where the anomaly increases sharply toward the north.

There would appear, therefore, to be a fairly definite relationship between the rock types as exposed at the surface and the major features of the anomaly field. In general, the more positive trends are associated with either basic volcanics, as in the Temiskaming provinces, or with the dense gneisses of the Grenville, while negative anomalies are associated with granitic rocks. From a quantitative point of view, little more can be done than to estimate the probable depth extent of the density differences, as the spacing of stations and the gradational nature of many of the boundaries prohibit a more detailed analysis.

The profile of Figure 2, which crosses the main trends perpendicularly and is representative of the anomaly variations, shows differences in anomaly level of about 40 milligals between the high and low areas. If we take the density difference between the granitic and denser rock types to be 0.15 gms./cc. (corresponding to 2.70 gms./cc. for granite gneiss, and 2.85 gms./cc. for biotite paragneiss and similar types) the depth extent required to produce this anomaly variation is 21,000 feet (6.4 kilometres). In other words, the characteristic rock types of the different regions may persist in depth through a significant proportion of the crust. Hodgson (1953) has deduced from a study of seismic waves from rock bursts that the crust beneath northern Ontario is single-layered, with a mean thickness of 35.4 kilometres.

The questions which now arise are the magnitude of the stresses developed in the crust due to these variations in anomaly, which persist over widths of several tens of miles, and the degree of isostatic compensation of the region as a whole. To illustrate an approach to these problems, two additional curves have been drawn on Figure 2. The first of these illustrates the level of Bouguer anomaly which would correspond to zero isostatic anomaly, on the Airy hypothesis for a depth of compensation of 40 kilometres. This curve has been obtained from the isostatic corrections given by Miller and Hughson (1936) for pendulum stations in Quebec and Ontario, and although it is reasonably well defined between Montreal and Parent, its character to the northwest is uncertain. The correction is rather slowly varying over the area of interest, and the curve indicates that in the vicinity of Parent and Oskelaneo a Bouguer anomaly of about minus 40 milligals would correspond to zero Airy anomaly. The second curve added to the figure is a sinusoidal variation, of wave-length 220 miles and amplitude 20 milligals, centred about a level of minus 56 milligals. It is rather remarkable how the sinusoidal curve approximates the main features of the observed anomaly profile over the central portion of the region. This is a convenient circumstance, for a harmonic, two-dimensional variation in gravity may be directly interpreted in terms of a corresponding harmonic surface distribution of mass, and for the latter case Jeffreys (1952, p. 188) has given the distribution of stress-difference required to support the loading.

It is well known that an anomaly variation of the form $\Delta g = C \sin mx$ where C is the amplitude, $m = 2\pi f$, and x is the distance in miles, may be produced by a surface distribution σ at a depth h, where

$$\sigma = \frac{C}{2\pi G} . e^{mh} . \sin mx, \text{ G being the gravitational constant.}$$

In the present case using the sinusoidal approximation, $\Delta g = 0.020 \sin 0.0285x$ in cm./sec.^{2}.

The corresponding surface distribution at a depth of 2 miles (roughly one-half the inferred depth extent of the structures) is

$$\sigma = \frac{0.020}{2\pi x 6.67 x 10^{-8}} . e^{2x0.0285} . \sin 0.0285x$$

$$\text{or} \quad \sigma = 5.1x10^4 \sin 0.0285x \quad \text{in gms./cm.}^2$$

Jeffreys points out that on an elastic theory for the crust, a surface loading of the form

$$\sigma = b \sin mx$$

gives rise to a stress difference which acquires a maximum value of

$$\frac{2gb}{e} \text{ at a depth } h = \frac{1}{m}.$$

With the above expression for σ, the corresponding maximum stress difference is 3.7×10^7 dynes/cm^2, at a depth of 37 miles below the surface. This is not large compared to the usually accepted figure for the strength of about 1.0×10^9 dynes/cm^2 for the crust itself (Jeffreys 1952, p. 196), but it is significant that the maximum value occurs some 15 miles beneath the base of the crust. The existence of such stresses, presumably since Precambrian time, would therefore be evidence of considerable strength in the sub-crustal rocks. However, the value obtained for this particular area is not in itself critical, for Jeffreys has shown that a strength up to 3.3×10^8 dynes/cm^2 to a depth of 600 kilometres is required to support even broader departures of the gravitational field from normal values.

The sinusoidal mass distribution investigated above is of course merely a convenient approximation. The form of the observed profile, however, does suggest the approximately equal areal extent of rock types of the high and low density types. The mean density of the upper 6 or 7 kilometres of the crust within this region of the Shield must therefore be in the neighbourhood of 2.78 gms/cc., rather than 2.67 gms./cc. usually quoted. Furthermore, since there is no reason to assume a decrease in density with depth, this may well represent the mean density of the entire upper portion of the crust under the area. The implication would be that beneath the depth of 6 or 7 kilometres, the material is, overall, rather homogeneous as to density, and that above this depth a separation into well marked belts of less dense granitic types, and denser, more basic rocks, has taken place. It is perhaps worth pointing out that the persistence of the negative trends over widths of several tens of miles is rather strong evidence against the formation of the lighter rock types by differentiation in place from a denser magma. For in this case, the still denser "basic pole" resulting from the differentiation process would be in the form of a broad sheet, whose excess attraction at points removed from the edges would nearly compensate for the mass deficiency in the overlying layer. The question is discussed in more detail when the anorthosite bodies are considered.

Returning to the curves of Figure 2, it is seen that in the vicinity of Parent the mean of the observed profile (approximately the axis of the sine curve at minus 56 milligals) is depressed some 16 milligals beneath the curve representing zero isostatic anomaly. In other words, the area as a whole appears to be over-compensated by an amount corresponding to an anomaly of 16 milligals, with the effects of density variations superimposed on this condition. Such an over-compensation could result from an excess crustal thickness of about 1 kilometre under the area in question which may well be a legacy from Precambrian mountain building.

The conclusion, therefore, is that the peculiar pattern of anomalies over this portion of the Shield, in which the intense negative effects are most prominent, is a result of the superposition of the contributions of major density differences upon an overall depressed Bouguer anomaly field. The granitic rocks give large negative effects because they are consistently less dense than the crust as a whole, the belts of granite being separated by regions of rocks denser than average. Crustal warping, if such a condition exists, is probably of such broad extent that it affects the major portion of the area to almost the same extent, and is not specifically related to the bodies of granite. The evidence being accumulated on anomalies over granites in many parts of the world (Bott 1953, Marshall and Narain 1954) supports the suggestion that granites are lighter than the crust as a whole, but it is admitted that the contributions of crustal deformation may be very different in different circumstances, as suggested by Marshall and Narain.

The Northern Boundary of the Grenville Sub-Province

The nature of the boundary between the Grenville and Temiskaming sub-provinces has been a subject of much discussion (Quirke and Collins, 1930; Gill 1948). Characteristically, the well-known rock types of the Temiskaming sub-province, that is, early Precambrian volcanic, sedimentary and intrusive rocks with a general east-west trend, are either cut off at the boundary, or pass through a narrow transition zone into Grenville gneisses with a northeasterly trending foliation. Norman (1936) described the relations in the Chibougamau region, where the Grenville rocks appear to be thrust over the older formations from the southeast, and suggested the presence of a continuous fault-zone extending from Lake Huron to beyond Lake Mistassini. Later writers have amplified this suggestion (Cooke, 1947; Wilson, 1948).

If the boundary does represent a major fault zone, evidence of this might be expected in the gravity anomalies, even with the rather open distribution of stations available.

In fact, the evidence is rather negative. There is a pronounced gravity gradient over the line of the presumed fault only in the region of Lake Chibougamau, where a band of Keewatin type lavas is known to end against the gneisses. There is no gravitational evidence of ultrabasic rocks being brought to the surface as there is along the Appalachian frontal thrusts discussed later.

It is perhaps significant that many of the major anomaly trends over the Grenville region are east-west, not northeast as is the foliation often observed in the rocks. Furthermore, the positive and negative trends are in line, approximately, with similar trends on the opposite side of the Grenville-Temiskaming boundary. For example, the prominent area of relatively high anomaly passing through Parent is in line with the major volcanic belt passing through Senneterre in the Temiskaming sub-province. To the north of this, the pronounced negative trend extends over both the "granites" of the Temiskaming and "granite gneiss" of the Grenville. It is possible, therefore, that in the Grenville sub-province the high and low density rock types were distributed along similar lines to those of the Temiskaming, and the northeast trend so often reported was subsequently impressed on this system by regional metamorphism.

It is obviously unsafe to draw further conclusions from the gravity observations alone, especially in view of the distribution of stations. The above discussion is not intended to suggest that a major fault separating the Grenville and Temiskaming regions does not exist. There is simply no direct evidence from the gravity anomalies for it, and there is evidence against any widespread emplacement of ultrabasic rocks along the boundary. Finally, the continuity of certain features of the anomaly map across the boundary suggest a certain original similarity in structural relationships between the denser gneisses of the Grenville and the volcanic and associated sedimentary rocks of the Temiskaming.

The Anorthosites

The area under study includes three well-known bodies of anorthosite: the Morin mass (Adams 1897) north of Montreal, a portion of the mass north and east of Lake St. John (Denis 1934; Ross 1949), and the smaller St. Urbain body (Mawdsley 1927), north of Baie St. Paul. Of the larger masses, only the Morin mass lies completely within the area of the gravity survey, but it is evident that both larger bodies lie within belts of highly negative Bouguer anomaly. Furthermore, the observations over the Morin body (Figure 3) show that a local, still more intense, negative anomaly occurs over the anorthosite. In other words, the anorthosite mass represents a body of even lower density than the surrounding rock types, which themselves are of the lighter Grenville types. It can only be concluded that the main mass, extending to depth, consists almost entirely of plagioclase or rock of comparable density, and that concentrations of ferromagnesian minerals are of infrequent occurrence through the volume of rock as a whole.

The question of the typical density of anorthosite is therefore of some importance and several measurements have been made on samples taken from the Morin body, as shown in Figure 4. Measurements of the density of the surrounding rocks are not shown on the map, but the mean of the densities of thirty-six samples of Grenville crystalline limestone, Trembling Mountain gneiss, and members of the Morin series other than anorthosite, is

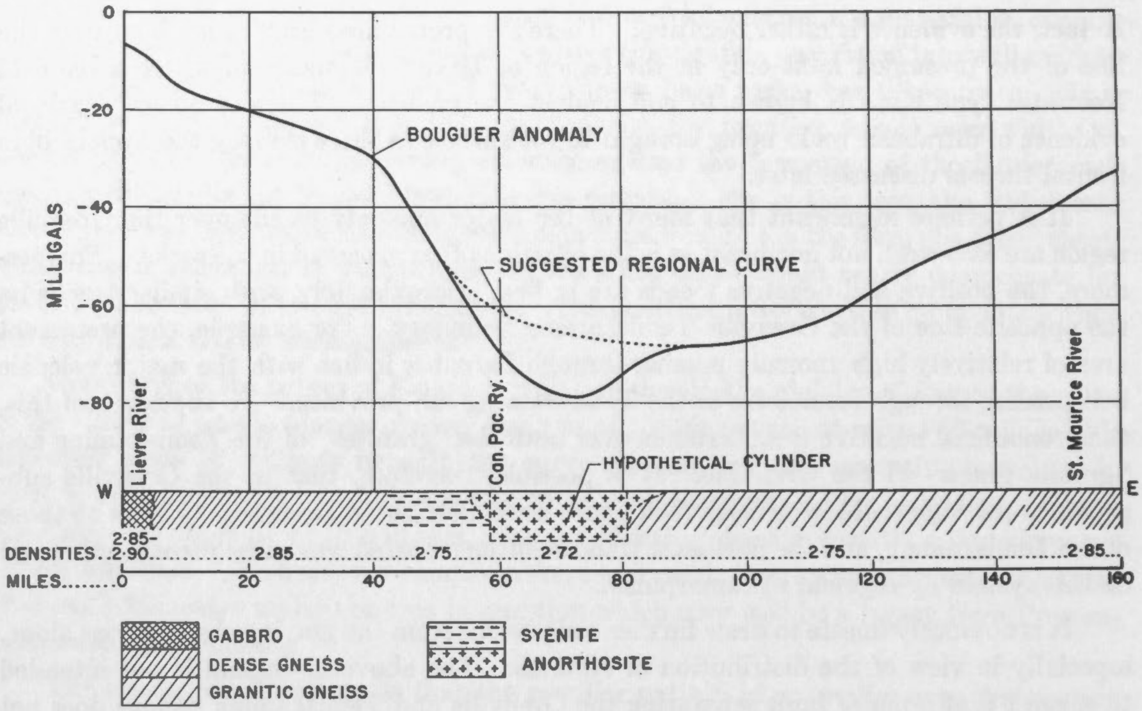

FIGURE 3.—Bouguer anomaly profile, St. Maurice River-Lièvre River

2.75 gms/cc. The range in density of rocks within the limits of the main body is from 2.65 gms/cc. for a coarsely-crystalline sample consisting almost entirely of plagioclase, to 3.08 gms/cc. for a sample high in ferromagnesium minerals. However, there is a suggestion from the diagram that the distribution of types is not random, but that the denser phase is most abundant in an area toward the south centre of the mass. If the distribution of types of density significantly greater than 2.70 gms. per cc. is as suggested by the broken line on the diagram, then a weighted mean density of the body as a whole (near the surface) would be about 2.72 gms./cc. In other words, the density contrast with the surrounding rocks may be of the order of 0.03 gms/cc., in which case a rock mass in the form of an approximately vertical cylinder would have to extend about 8 miles in depth to explain the observed negative anomaly. These relationships are indicated in Figure 3.

It is significant that the anorthosite appears to be of lower density than the surrounding rocks, and that the body must extend to such depth. Many of the theories for the origin of anorthosite assume that plagioclase crystals accumulated during the differentiation of an intermediate or basic parent magma (Bowen 1917, Grout 1928, Balk 1931). The evidence of the gravity anomalies would rule against the presence of a basic layer beneath the anorthosite, as suggested by Bowen, or against the presence of masses of gabbro throughout the body, as in Balk's view. It would be virtually impossible, for example to interpret the local negative anomaly over the Morin body by a differentiated sill of any reasonable thickness. Whatever thickness of the light phase was assumed, the basic layer beneath would have to be taken proportionately thicker, depending on the assumed composition of the parent magma. If this body has originated through differentiation, the denser material must have been removed laterally, beyond the limits of the negative anomaly.

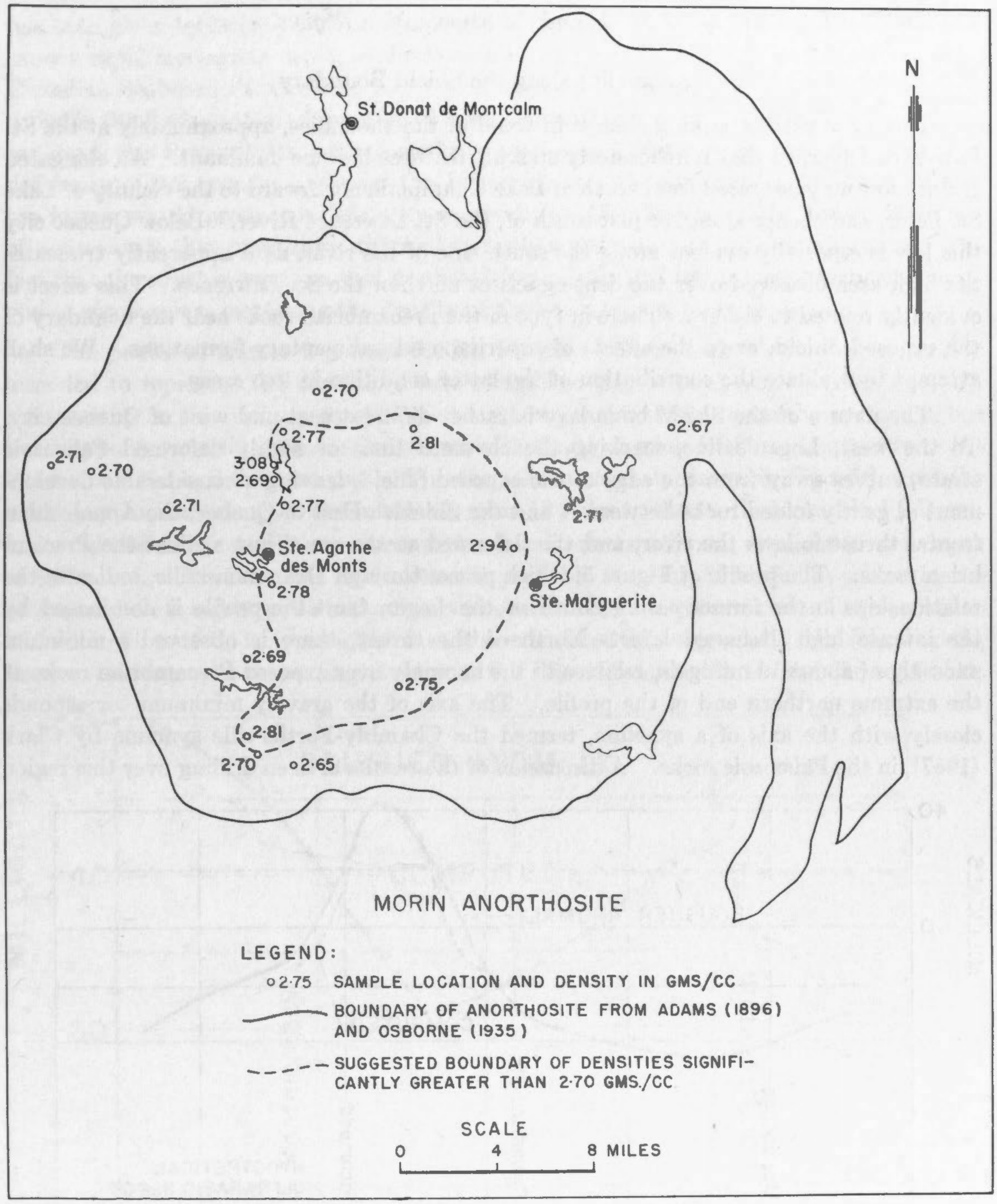

FIGURE 4.—Distribution of densities in Morin anorthosite

There may be further significance in the fact that the large bodies of anorthosite occur in the two general belts of the lower density, granitic rock types of the Grenville. In other words, there may have been conditions existing along these lines which were favourable to the formation, or emplacement, of both granite and anorthosite. The St. Urbain body, whose mean diameter is about 12 miles, occurs in an area of the denser type of gneisses, and may have had a somewhat different origin than the larger masses. It does, however, produce a local decrease of the Bouguer anomaly.

The Southern Boundary of the Shield and the Appalachian Region

Anomalies along the Shield Boundary

There is a rather striking change in trend of the anomalies, approximately at the St. Lawrence River, so that northeasterly striking features become dominant. An elongated gravity low may be traced from north of Lake Champlain northward to the vicinity of Lake St. Peter, and thence along, or just south of, the St. Lawrence River. Below Quebec city this low is especially evident along the south side of the river, as it apparently truncates the high area observed over the dense gneisses north of the St. Lawrence. This effect is evidently related to either a change in type of the Precambrian rocks near the boundary of the exposed Shield, or to the effects of superimposed sedimentary formations. We shall attempt to evaluate the contribution of the latter condition in two areas.

The nature of the Shield boundary is rather different east and west of Quebec city. To the west, Logan's line, marking the northern limit of highly deformed Palæozoic strata, curves away from the edge of the exposed Shield, leaving a considerable development of gently folded rocks between it and the Shield. East of Quebec, the Appalachian frontal thrust follows the river, and the deformed strata are thrust against the Precambrian rocks. The profile of Figure 5, which passes through Drummondville, indicates the relationships in the former case. South of the Logan fault the profile is dominated by the intense high discussed later. North of the thrust, there is observed a minimum anomaly of about 10 milligals, relative to the anomaly over exposed Precambrian rocks at the extreme northern end of the profile. The axis of the gravity minimum corresponds closely with the axis of a syncline, termed the Chambly-Fortierville syncline by Clark (1947), in the Palæozoic rocks. A discussion of the results of deep drilling over this region

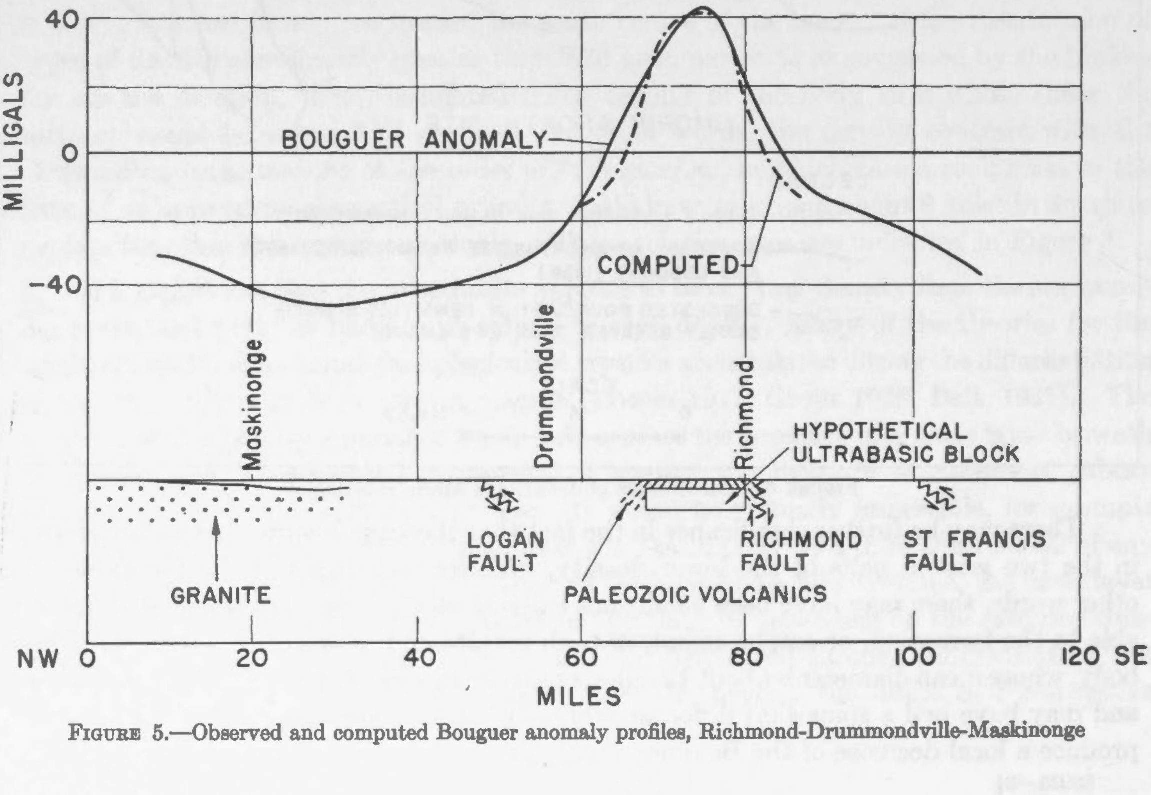

FIGURE 5.—Observed and computed Bouguer anomaly profiles, Richmond-Drummondville-Maskinonge

has been given by Belyea (1952). In particular, two wells drilled south of Trois Rivières show a rapid increase in depth to the Precambrian toward the axis of the syncline. The Canadian Seaboard St. Gregoire No. 1 well, approximately on the axis of the structure, ended in the Beekmantown formation of lower Ordovician age at a depth of 5,040 feet below sea level; the Precambrian surface could be well over 1,000 feet deeper. For a density deficiency of 0.2 gms./cc. between the Palæozoic and Precambrian rocks, 6,000 feet of the former would produce a deficiency in gravity of 15 milligals. The known thickness of sediments is thus more than sufficient to explain the observed gravity minimum. The fact that the effect is less than that predicted is probably due to the well-known phenomenon of compaction, increasing the density of the sedimentary rocks at depth.

The profile of Figure 6 crosses the St. Lawrence River near Montmorency, and is intended to represent the conditions east of Quebec city. As shown by Alcock (1947), the structure in this vicinity consists of at least two major thrusts from the southeast, but for simplicity we may examine the effects of a single dipping fault contact between the Palæozoic rocks and the basement. The decrease in anomaly shown in Figure 6, from the vicinity of Montmorency to the minimum some 12 miles to the south, is practically linear, and would be satisfactorily consistent with a frontal thrust dipping at about 5° to a depth of 6,700 feet. However, this explanation is probably too simplified, for as shown in the diagram, there is a greater decrease observed over the Precambrian rocks as the edge of the Palæozoic formations is approached than the calculated effect predicts. In other words, there is evidence of a decreasing density in the Precambrian rocks toward the southeast,

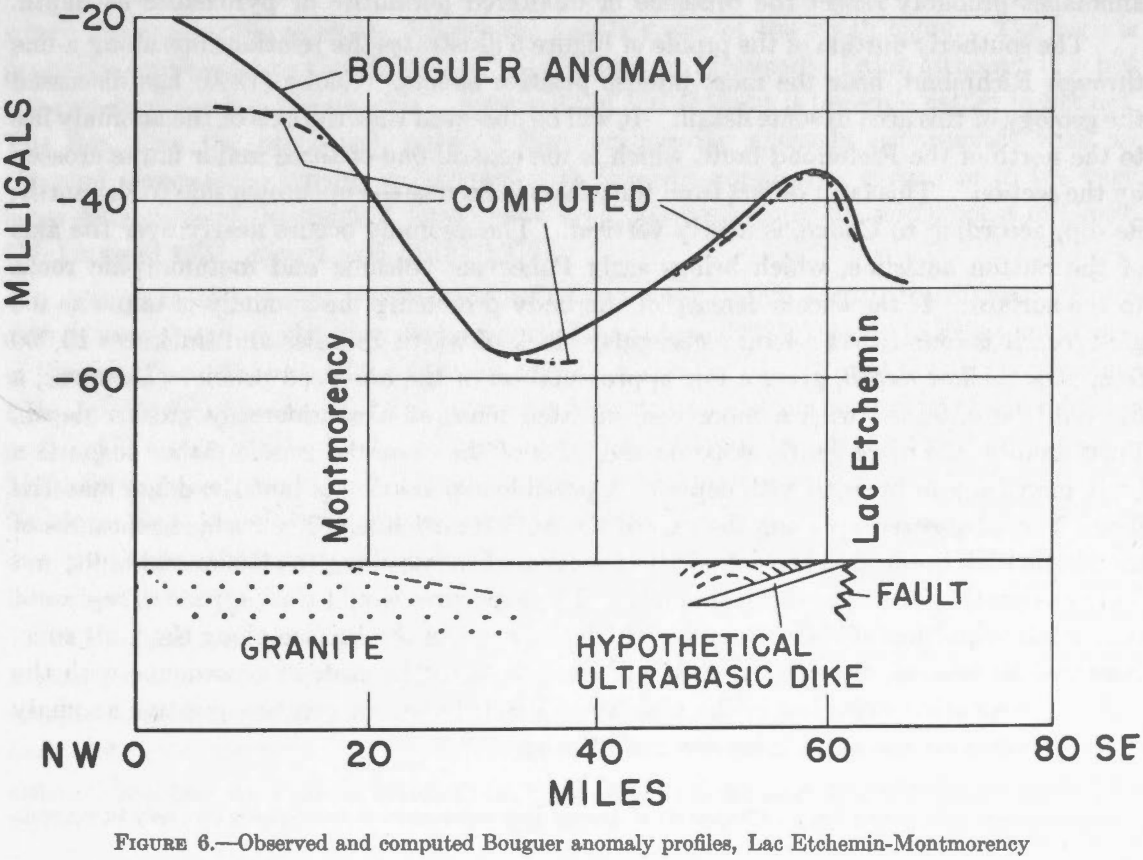

FIGURE 6.—Observed and computed Bouguer anomaly profiles, Lac Etchemin-Montmorency

and this is very probably influencing the form of the profile. Nevertheless, the striking parallelism of the axis of the gravity low to Logan's line along the St. Lawrence River below Quebec suggests that at least a major part of the gravity deficiency is due to the Palæozoic formations thrust against the Shield. The low is thrown into prominence as a narrow strip between the Shield and the area of high gravity which lies about 30 miles southeast of the St. Lawrence, discussed in the following section.

The Positive Anomalies of the Eastern Townships and Gaspé

The pronounced positive anomalies of southern Quebec lie along an axis which lies south of the northern limit of the Appalachian region and extends from the International Boundary to the end of Gaspé peninsula. However, the positive trend is interrupted in the region of St. Pamphile, east of Quebec city, and two detached high areas are therefore seen on the map. The more southerly of these is most intense in the district between Waterloo, Richmond and Thetford Mines, and would appear to be related to the well-known ultrabasic rocks in this vicinity.*

The ultrabasic rocks of southern Quebec have been well described in the literature (Dresser 1913, Cooke 1937). As many of the exposures are serpentinized, the general area has been referred to as the Serpentine Belt. However, the mineral serpentine has a density of only about 2.5 gms./cc., and large bodies of this material in Palæozoic rocks would not produce the striking positive anomalies. There must therefore be a limit to the depth below the present surface to which serpentinization has taken place. The gravity anomalies probably reflect the presence of unaltered peridotite or pyroxenite at depth.

The southerly portion of the profile of Figure 5 illustrates the relationships along a line through Richmond, near the most intense positive effects. Cooke (1950) has discussed the geology of this area in some detail. It will be observed that the axis of the anomaly lies to the north of the Richmond fault, which is the central one of three major faults crossed by the section. This fault differs from the others in having the upthrown side to the north; its dip, according to Cooke, is nearly vertical. The anomaly occurs nearly over the axis of the Sutton anticline, which brings early Palæozoic volcanic and metamorphic rocks to the surface. If the excess density of the body producing the anomaly is taken as 0.5 gms./cc., it is found that a long rectangular block of width 13 miles and thickness 10,000 feet, at a shallow depth, gives a fair approximation of the observed profile. However, a fit could be obtained with a more concentrated mass at a considerably greater depth. Furthermore, the more gentle slope on the sides of the observed profile rather suggests a body increasing in breadth with depth. A possible explanation is that the dense material forms a core squeezed up along the axis of the Sutton anticline. The surface exposures of ultrabasic rock in the area are actually in the form of sheets along the Richmond fault, and lie to the south of the axis of the anomaly. The exposures would thus appear to represent only a minor portion of the main mass which has reached the surface along the fault zone. North of Richmond, the positive axis curves sharply to the east, in accordance with the exposed Serpentine Belt, and in the vicinity of Black Lake, the greatest positive anomaly is coincident with the surface exposure of ultrabasic rocks.

*The specific relationships in the area between the Richelieu and Chaudière Rivers are the subject of a detailed investigation by Professor M. M. Fitzpatrick of Queens' University and will be discussed here only to complete the regional picture.

Northeast of Thetford Mines, the exposures are much less frequent, and the extent of the Serpentine Belt, as determined by surface mapping, is somewhat uncertain. The continuity of the belt has been largely established by the aeromagnetic maps of the Geological Survey of Canada which indicate a distinct positive trend extending toward St. Pamphile. The gravity observations confirm the suggestion of a continuous structure, and in addition throw more light on the depth extent and form of the anomalous body.

Examination of the gravity map shows that the positive trend decreases rather uniformly from the Chaudière River until it practically disappears southwest of St. Pamphile, The profile of Figure 6 indicates the nature of the anomaly in the vicinity of Lac Etchemin. with the major geological features as mapped by Tolman (1936). Small bodies of serpentine are found in the vicinity of the fault shown, which brings the older Caldwell group on the north in contact with Beauceville strata on the south. The peak of the gravity anomaly is observed near the trace of this fault, but the asymmetry of the curve strongly suggests a body dipping to the north beneath the Sutton anticlinal axis a few miles to the northwest. For comparison, the computed profile of a dyke-like structure dipping to the north at 15° is shown. The presence of a northwesterly dipping body may seem strange in a region where the major thrusts are from the southeast, but the asymmetry of the positive anomaly is quite marked, as far as the effect can be traced. It would appear to suggest that the location of the ultrabasic rocks is controlled at depth by the Sutton anticline, and at the surface by the fault which forms the southerly boundary of the older rocks.

The positive area in Gaspé is most intense near the easterly end of the peninsula, where the axis of the anomaly follows the gentle curve of the north shore. The high is probably continuous to the vicinity of Val Brillant on Matapedia Lake, although it is not completely defined in the interior. Southeast of Val Brillant it becomes rather indistinct. The fact that the prominent positive Bouguer gravity anomaly corresponds with an elevated topographic region, in contrast with isostatic conditions, gives rise to the very large deflections of the vertical which have been observed along the north coast of Gaspé (McDiarmid 1931, Alcock and Miller 1932).

Along the line of the positive anomaly lie several known serpentine masses. From east to west there are the Mount Serpentine body (Jones 1935), about 15 miles northwest of Gaspé village; Mount Albert (Alcock 1926); two bodies near Mount South (McGerrigle 1954), about 16 miles south of Ste. Anne des Monts: and a small body west of Lake Matapedia (Aubert de la Rue 1941). These bodies are believed by McGerrigle to be of post-Midddle Silurian, pre-Middle Devonian age. They may possibly be related to thrust faulting along the northerly side of Gaspé peninsula (McGerrigle 1953), faulting which has brought the pre-Ordovician Shickshock group in contact with Lower Ordovician sedimentary rocks on the north.

The most complete profile across the gravity anomaly is that obtained south of Matane, as shown in Figure 7. In this vicinity the peak of the curve is quite narrow and sharply defined, suggesting a source at no great depth. The curve displays also a marked asymmetry, decreasing much more rapidly on the north side. For comparison, the computed effect is shown for a dyke-like sheet of material with excess density 0.5 gms./cc., thickness 1.5 miles, and dip 30° toward the south. The calculated curve fits the observa-

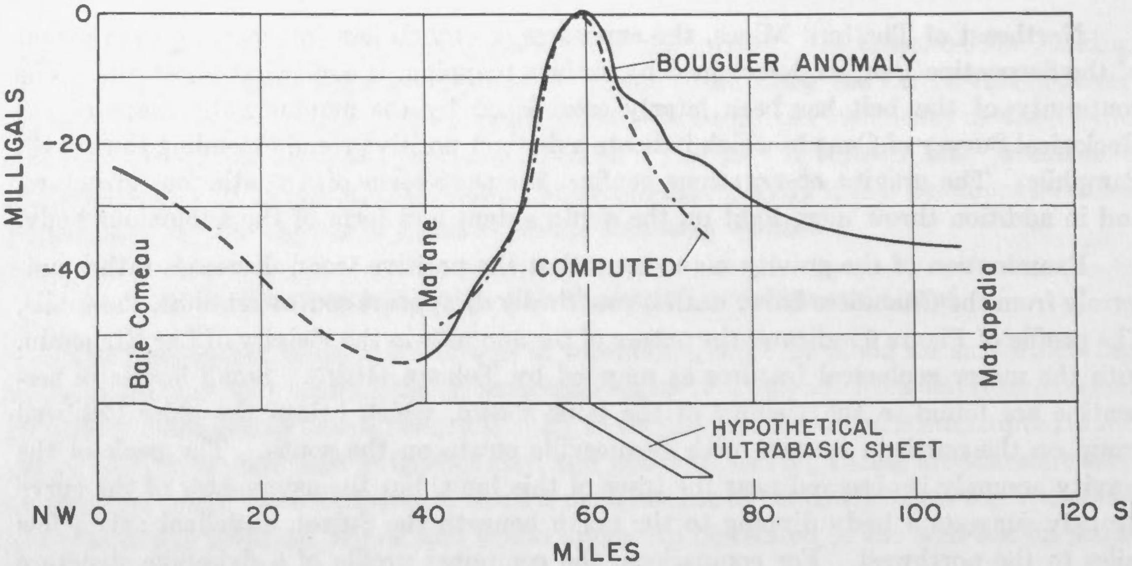

FIGURE 7.—Observed and computed Bouguer anomaly profiles, Matapedia-Matane-Baie Comeau

tions fairly well, except toward the southerly end of the profile. One might be tempted to assume a body with flatter dip to improve the fit, but the "shoulders" on the observed profile suggest the presence of subsidiary bodies on the south, and it is probably unwise to push the interpretation further. In any case, southerly dip, and depth extent to about 10 miles, are indicated. The surface rocks along the line of the profile consist almost entirely of steeply dipping shales, sandstones, quartzite and conglomerate of Lower Ordovician (Sillery) age (Aubert de la Rue 1941). There would be nothing in the lithology to suggest the rapid increase in anomaly from Matane southward. However, the axis of maximum anomaly is in direct line with the small exposure of serpentinized peridotite 12 miles southwest of Lake Matapedia.

If the interpretation offered above is correct, and if the structure is continuous between the actual lines of stations, the ultrabasic material underlying Gaspé peninsula would be in the form of a southerly dipping sheet, curved so that its surface trace parallels the north shore (and other structures), and thinning toward the west.

There appears to be no doubt that near surface concentrations of dense material are missing in the vicinity of St. Pamphile, so that there is in fact a gap of at least 30 miles between the Gaspé and Eastern Township belts. It is not obvious from the overall structure why the amounts of ultrabasic rock which have been brought to moderate depths should decrease with distance from both the Richmond-Thetford and Gaspé areas, and finally disappear in this region.

General Conclusions

The interpretation of the Bouguer anomalies has led to certain broad conclusions regarding structures in the Precambrian Shield and northern Appalachian regions. It may be useful to summarize these in this place.

(1) The chief anomaly trends over the Precambrian Shield are believed to be caused by systematic differences in density extending well into the crust. The extreme densities encountered are about 2.70 or less for granitic types, and 2.85 gms./cc. for dense paragneiss or basic volcanic rocks, depending on the particular province of the Shield. As the volumes

of each general type have been shown to be roughly equal, it is suggested that the mean density of the upper portion of the crust under the area in question is closer to 2.78 gms./cc. than the 2.67 or 2.70 gms./cc. often quoted. Granite batholiths thus represent emplacements in the crust of material less dense than the crust as a whole.

(2) The negative anomalies are especially prominent because the mean anomaly level in the central part of the Shield area studied, appears to be about 16 milligals less than that consistent with zero isostatic anomaly. It is suggested that this may represent the effect of an incomplete adjustment following the erosion of Precambrian mountains.

(3) No outstanding gravitational effects are observed over the line of the presumed Huron-Mistassini or Grenville front thrust. The strike of certain major anomalies in the Grenville sub-province is east-west, and approximately in line with similar effects observed over the Temiskaming province northwest of this line.

(4) The major anorthosite bodies covered by the observations are shown to be even less dense than the granitic rocks into which they appear to be intruded. It is felt that no process of differentiation in place from an intermediate or basic magma would be consistent with these observations.

(5) Belts of positive anomaly in southeastern Quebec are taken to indicate the presence, at moderate depths, of ultrabasic rocks whose scattered surface exposures form the well-known Serpentine Belt. The trend is shown to be nearly continuous from the international border to the end of Gaspé peninsula, but there is a definite gap, roughly south of the mouth of the Saguenay River. In the Eastern Townships, the form of the profiles studied suggest that the bulk of the dense material may occupy the core of the Sutton anticline, although the material which has reached the surface has followed a fault bounding the anticlinal structure on the south. In the Gaspé area, a southerly dipping sheet is suggested, which may owe its location to thrust faults, including the prominent one bounding the Shickshock Mountains on the north. Assuming the adopted density contrast is valid at depth, a vertical depth extent of about 10 miles is suggested for the sheet.

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APPENDIX A

The Principal Facts

PRINCIPAL FACTS FOR GRAVITY STATIONS

Road Traverse—1945 South of St. Lawrence River around Gaspé Peninsula HUMBLE

Station No.	Station Name	Longitude °	Longitude ′	Latitude °	Latitude ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	Lac au Saumon	67	20.6	48	25.0	502	980.8862	−.0038	−.0209
	Sayabec		40.7		33.3	580	.8969	.0019	−.0179
	Bic	68	42.0		22.3	79	.8875	−.0382	−.0409
	St. Fabien		52.1		17.4	447	.8582	−.0256	−.0408
	Metis Beach	67	59.3		40.4	80	.9050	−.0477	−.0504
	Baie des Sables		52.2		43.9	35	.9124	−.0497	−.0509
	St. Ulrich		41.7		47.4	28	.9168	−.0512	−.0521
	Matane		31.6		50.9	25	.0205	−.0530	−.0539
	Ste. Félicité		20.3		53.8	53	.9244	−.0508	−.0526
	Grosses Roches		10.4		56.0	80	.9279	−.0481	−.0508
	Les Méchins	66	58.8		59.6	78	.9363	−.0452	−.0478
	Capucins		50.9	49	02.2	15	.9446	−.0467	−.0472
	Cap Chat		41.3		05.4	70	.9499	−.0410	−.0434
	Ste. Anne des Monts		29.1		07.1	17	.9654	−.0330	−.0336
			20.0		10.3	90	.9753	−.0210	−.0241
	Ste. Marthe		10.6		11.9	25	.9979	−.0069	−.0078
	Ruisseau Arbour	65	57.0		13.5	40	981.0050	−.0007	−.0021
	Rivière à Claude		53.8		12.8	25	.0033	−.0028	−.0037
	Mont Louis		44.3		13.5	15	.0097	.0016	.0011
			29.5		14.9	870	980.9658	.0360	.0064
			16.3		13.5	700	.9777	.0340	.0102
			03.8		13.1	263	981.0115	.0273	.0184
		64	46.3		08.6	455	980.9972	.0378	.0223
			33.2		04.2	370	.9964	.0355	.0229
	Fox River		23.5	48	59.2	50	981.0073	.0238	.0221
	Griffin Cove		18.4		55.3	60	980.9983	.0215	−.0195
	Cap des Rosiers		12.6		51.5	40	.9900	.0171	.0158
	Cap des Rosiers		12.6		51.2	45	.9894	.0173	.0153
	Gaspé		29.1		49.1	71	.9880	.0215	.0191
	Douglastown		23.1		45.5	11	.9840	.0172	.0169
	St. Georges		14.7		39.5	168	.9613	.0183	.0126
	Percé		13.3		31.2	76	.9537	.0144	.0119
	Percé Sta.		18.9		27.8	101	.9381	.0062	.0028
	Grande Rivière		29.7		23.5	56	.9329	.0033	.0014
	Chandler		40.5		20.2	2	.9334	.0036	.0035
	Newport		45.0		15.7	37	.9251	.0053	.0040
	Gascons		52.0		11.8	117	.9059	−.0005	−.0045
	Black Cape	65	49.3		07.9	78	.9004	−.0039	−.0065
	Port Daniel	64	59.3		10.5	9	.9070	−.0077	−.0080
	St. Godefroy	65	07.4		05.1	77	.8914	−.0088	−.0114
	Paspébiac		15.3		01.9	186	.8790	−.0061	−.0124
	Bonaventure		28.2		03.0	62	.8927	−.0058	−.0079
	Caplan		40.8		06.2	87	.8967	−.0042	−.0072
	Maria	66	00.3		10.5	28	.8967	−.0162	−.0171
	Carleton		08.0		07.0	48	.8989	−.0069	−.0085
	Nouvelle		18.6		08.0	49	.8926	−.0146	−.0163
	Escuminac		28.5		07.4	22	.8828	−.0260	−.0268
	Oak Bay		37.3		03.3	55	.8705	−.0290	−.0309
	St. Jean	73	15.1	45	18.0	105	.6260	−.0205	−.0241
	Chambly Canton		16.1		26.4	76	.6421	−.0199	−.0224
	Rougemont		03.9		26.3	167	.6362	−.0171	−.0228
	Abbotsford	72	53.6		26.1	207	.6303	−.0189	−.0260

PRINCIPAL FACTS FOR GRAVITY STATIONS

Road Traverse—1945 South of St. Lawrence River — HUMBLE

Station No.	Station Name	Longitude °	Longitude ′	Latitude °	Latitude ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	Eastray	72	20.6	45	18.4	911	980.5988	.0275	−.0035
	Coaticook	71	48.3		08.0	957	.5337	−.0177	−.0503
	Ayer's Cliff	72	02.3		10.2	559	.5722	−.0199	−.0390
	Caughnawaga	73	40.7		24.9	88	.6431	−.0155	−.0185
	Pointe Claire		49.5		25.6	81	.6458	−.0145	−.0172

Road Traverse 1945—North of St. Lawrence River
In vicinity of Lake St. John and Mont Laurier — HUMBLE

Station No.	Station Name	Longitude °	Longitude ′	Latitude °	Latitude ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
		70	03.0	47	56.5	753	980.8270	.0032	−.0224
	Lake Deschênes		04.3		57.3	758	.8260	.0016	−.0242
			01.8	48	05.1	432	.8548	−.0120	−.0267
	Petit Saguenay R.		04.5		12.8	55	.8801	−.0336	−.0355
	Rivière St. Jean		16.4		12.7	328	.8587	−.0292	−.0404
	Rivière Eternité		23.8		15.2	625	.8467	−.0170	−.0383
	St. Félix d'Otis		37.5		16.6	764	.8330	−.0197	−.0458
	Port Alfred		52.8		20.1	28	.8700	−.0573	−.0582
	Chicoutimi	71	03.8		25.8	21	.8689	−.0675	−.0682
	Chicoutimi (pend)		03.8		25.7	75	.8648	−.0663	−.0689
	Jonquière		15.2		24.7	487	.8446	−.0463	−.0629
	(Samson)		24.3		26.0	580	.8455	−.0386	−.0584
	Labarre		35.6		27.2	537	.8446	−.0454	−.0637
	St. Joseph d'Alma		39.4		33.0	302	.8650	−.0557	−.0660
	Metabetchouan		52.3		25.7	359	.8561	−.0483	−.0606
	Chambord	72	03.0		26.0	551	.8435	−.0434	−.0621
	Roberval		13.1		30.9	350	.8587	−.0544	−.0663
	St. Prime		19.5		35.7	351	.8635	−.0567	−.0686
	Normandin		30.3		49.6	419	.8710	−.0635	−.0778
	St. Félicien		26.9		39.0	368	.8659	−.0576	−.0701
	Dolbeau		13.6		52.6	414	.8761	−.0634	−.0775
	Péribonca		02.9		45.9	348	.8698	−.0659	−.0777
	Honfleur	71	50.9		44.7	371	.8742	−.0575	−.0701
	St. Henri de Taillon		49.4		39.7	401	.8678	−.0536	−.0672
	St. Coeur de Marie		42.0		38.0	391	.8673	−.0525	−.0658
	Park Gate		40.6		15.7	1245	.7918	−.0144	−.0568
	Sawine River		34.6		07.8	1390	.7811	.0003	−.0470
	Le Gîte		32.1		05.6	1800	.7531	.0142	−.0471
			24.5	47	57.8	1740	.7400	.0072	−.0521
			17.1		45.4	2530	.6892	.0493	−.0369
			14.5		37.6	2630	.6773	.0585	−.0311
	Le Relais		14.2		31.3	2720	.6701	.0691	−.0235
			11.4		24.3	2655	.6730	.0764	−.0140
			13.4		14.1	2360	.6723	.0633	−.0171
	S. Park Gate		15.7		09.7	1870	.6934	.0449	−.0188
	Stoneham		21.5	46	59.0	550	.7536	−.0030	−.0217
	Charlesbourg		16.1		52.1	375	.7449	−.0178	−.0306
	St. Augustin		28.0		45.4	212	.7434	−.0246	−.0318
	Neuville		35.1		42.6	226	.7386	−.0238	−.0315
	Donnacona		43.9		40.3	31	.7482	−.0291	−.0301
	Grondines	72	02.5		37.7	121	.7436	−.0213	−.0254

PRINCIPAL FACTS FOR GRAVITY STATIONS

Road Traverse—1945 North of St. Lawrence River

Station No.	Station Name	Longitude °	Longitude ′	Latitude °	Latitude ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	La Pérade	72	12.5	46	34.6	39	980.7424	−.0256	−.0270
	Champlain		21.6		27.3	43	.7237	−.0330	−.0344
	Cap de la Madeleine		30.0		22.4	55	.7145	−.0336	−.0355
	Pointe du Lac		41.3		17.7	62	.6996	−.0409	−.0430
	Yamachiche		50.0		17.2	30	.6996	−.0431	−.0441
	Maskinongé	73	01.2		13.5	48	.6965	−.0390	−.0406
	St. Lin		45.4		51.2	210	.6692	−.0174	−.0246
	New Glasgow		52.5		50.2	242	.6672	−.0149	−.0232
	Ste. Thérèse		50.3		38.5	143	.6499	−.0239	−.0288
	Shawbridge	74	05.7		52.3	595	.6463	−.0058	−.0261
	Val Morin		10.3		00.6	1018	.6024	−.0224	−.0571
	Ste. Agathe		17.0		03.1	1207	.5860	−.0248	−.0659
	Nantel		24.1		06.3	1264	.5794	−.0308	−.0739
	Modes Creek		43.7		10.7	705	.6389	−.0305	−.0545
	Labelle		44.0		17.0	749	.6401	−.0346	−.0602
	l'Annonciation		52.5		25.0	816	.6418	−.0386	−.0664
	Nominingue	75	01.7		23.6	835	.6472	−.0294	−.0578
	(Lac Jaquay)		08.9		29.9	1050	.6402	−.0256	−.0614
	"		08.9		30.0	1078	.6405	−.0229	−.0596
	Val Barette		21.3		30.5	792	.6608	−.0302	−.0572
	Mont Laurier		29.4		33.4	731	.6701	−.0310	−.0559
	Ferme Neuve		27.0		42.0	719	.6872	−.0280	−.0525
	Mont St. Michel		20.1		47.0	907	.6792	−.0258	−.0567
	St. Anne du Lac		19.6		52.8	873	.6990	−.0179	−.0476
	Lac Gatineau		43.0		33.6	850	.6831	−.0071	−.0361
	St. Famille d'Aumond		54.0		27.6	644	.6904	−.0102	−.0322
	Messines	76	01.3		14.5	571	.6814	−.0063	−.0257
	Gracefield		03.3		05.6	508	.6719	−.0084	−.0257
	Kazabazua		03.4	45	57.1	601	.6589	.0001	−.0203
	Venosta		01.4		52.1	549	.6526	−.0036	−.0223
	Farrelton	75	54.9		44.9	346	.6498	−.0146	−.0263
	Wakefield		55.8		38.4	330	.6349	−.0213	−.0325
	Kirk's Ferry		48.9		32.6	340	.6219	−.0241	−.0361
	Ironsides		44.8		28.4	186	.6325	−.0221	−.0284
	E. Templeton		36.4		29.7	160	.6468	−.0123	−.0177
	Thurso		14.7		35.9	186	.6521	−.0138	−.0201
	Plaisance		06.8		36.5	184	.6399	−.0271	−.0334

Road Traverse 1946 Chapeau to Ottawa along North Shore of Ottawa River — ATLAS

Station No.	Station Name	Longitude °	Longitude ′	Latitude °	Latitude ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	Chapeau	77	04.5	45	55.0	359	980.6476	−.0307	−.0430
	Waltham	76	54.5		54.6	368	.6557	−.0212	−.0337
	Davidson		45.9		52.2	365	.6374	−.0162	−.0286
	Fort Coulonge		44.3		50.4	367	.6561	−.0146	−.0271
	Vinton		36.9		47.0	368	.6521	−.0134	−.0259
	Campbells Bay		36.2		44.0	363	.6527	−.0088	−.0211
	Shawville		29.5		36.3	571	.6290	−.0013	−.0207
	Wyman		18.1		31.8	398	.6257	−.0141	−.0276
	Quyon		14.4		31.3	279	.6276	−.0227	−.0322
	Breckenridge	75	57.3		28.9	219	.6280	−.0243	−.0318

PRINCIPAL FACTS FOR GRAVITY STATIONS

Road Traverse 1946 South of St. Lawrence River in Eastern Townships

ATLAS

Station No.	Station Name	Longitude °	Longitude ′	Latitude °	Latitude ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	St. Bruno	73	20.8	45	30.8	74	980.6564	−.0123	−.0149
	St. Basil		17.3		31.7	58	.6584	−.0132	−.0152
	Ste. Madeleine		05.7		35.6	111	.6481	−.0245	−.0282
	Ste. Rosalie	72	54.2		38.4	112	.6524	−.0243	−.0281
	Ste. Rosalie (Stn.)		54.6		38.3	112	.6516	−.0249	−.0287
	St. Eugene		41.9		48.3	270	.6596	−.0171	−.0263
	St. Eugene (Stn.)		39.2		46.7	272	.6659	−.0082	−.0175
	St. Germain		33.3		50.3	264	.6652	−.0151	−.0241
	Drummondville		29.5		52.8	290	.6615	−.0200	−.0299
	St. Cyril		25.4		55.8	285	.6599	−.0266	−.0363
	N.D. du Bon Conseil		20.6	46	00.1	271	.6627	−.0316	−.0408
	St. Léonard Jct.		22.3		06.4	243	.6707	−.0357	−.0440
	Nicolet		36.3		13.5	67	.6923	−.0414	−.0437
	Nicolet		36.3		13.5	69	.6924	−.0411	−.0435
	La Baie		42.9		08.0	82	.6812	−.0428	−.0456
	Pierreville		48.8		04.1	77	.6760	−.0426	−.0452
	Yamaska		54.8		00.1	54	.6747	−.0400	−.0419
	Sorel	73	06.9		02.4	44	.6824	−.0368	−.0383
	St. Ours		09.1	45	53.3	49	.6708	−.0342	−.0359
	St. Denis de Richelieu		09.7		47.1	50	.6642	−.0314	−.0331
	St. Charles R. Richelieu		11.3		41.4	41	.6590	−.0288	−.0302
	St. Mathias		16.1		28.4	45	.6470	−.0209	−.0224
	Lawrenceville	72	20.4		25.4	704	.6369	.0355	.0115
	Racine		15.1		30.3	894	.6365	.0456	.0151
	Kinsey Falls		04.4		51.5	391	.7070	.0369	.0236
	Warwick	71	59.3		56.6	480	.7018	.0325	.0161
	St. Albert	72	05.4	46	00.1	380	.6835	−.0006	−.0135
	St. Clothilde		14.2	45	59.4	305	.6723	−.0178	−.0282
	Princeville	71	52.5	46	10.2	528	.6768	−.0085	−.0265
	N.D. de Lourdes		49.3		19.6	388	.6848	−.0278	−.0410
	Warden	72	30.3	45	22.8	670	.6449	.0442	.0214
	Adamsville		46.9		16.1	376	.6035	−.0147	−.0275
	Cowansville		45.0		12.4	345	.6000	−.0155	−.0273
	Farnham		58.5		16.9	193	.6121	−.0245	−.0311
	Ste. Brigide d'Iberville	73	03.9		19.3	157	.6193	−.0243	−.0297
	Richelieu		16.0		26.8	85	.6410	−.0207	−.0236
	Beaconsfield		50.9		26.1	108	.6445	−.0140	−.0177

Road Traverse 1947 between Timiskaming and Rouyn

ATLAS

Station No.	Station Name	Longitude °	Longitude ′	Latitude °	Latitude ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	Timiskaming (Ry. Stn.)	79	05.7	46	43.1	742	980.6882	−.0265	−.0517
	Timiskaming (pend)		06.0		43.0	834	.6816	−.0243	−.0527
	Dozois		08.6		50.3	772	.7013	−.0214	−.0477
	Laniel		16.2	47	02.6	880	.7118	−.0191	−.0491
	Fabre		22.0		12.0	737	.7468	−.0117	−.0368
	Baie d'Africain		23.7		14.4	595	.7595	−.0159	−.0362
	Ville Marie		26.5		19.8	640	.7646	−.0147	−.0365
	Ville Marie		26.1		19.8	660	.7642	−.0132	−.0357
	Ville Marie		26.7		19.9	630	.7650	−.0154	−.0369
	(Fabre)		21.9		06.6	827	.7210	−.0209	−.0491

PRINCIPAL FACTS FOR GRAVITY STATIONS

Road Traverse 1947 — ATLAS

Station No.	Station Name	Longitude ° ′	Latitude ° ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	(Fabre)	79 22.1	47 07.1	776	980.7252	−.0223	−.0487
	(Fabre)	22.5	08.4	810	.7258	−.0204	−.0480
	(Fabre)	22.6	09.1	813	.7259	−.0211	−.0488
	Lavallée River	22.2	10.8	725	.7387	−.0191	−.0438
	(Baie d'Africain)	24.2	15.6	745	.7495	−.0136	−.0390
	Miron	25.2	17.6	690	.7572	−.0141	−.0268
	Lorrainville	20.1	21.2	767	.7688	−.0007	−.0268
	(Ville Marie)	26.2	22.1	715	.7670	−.0086	−.0330
	(Guigues)	26.9	24.5	743	.7604	−.0163	−.0416
	(Guigues)	26.2	26.1	708	.7664	−.0159	−.0400
	Guigues	26.2	27.8	744	.7778	−.0037	−.0291
	(Guigues)	26.0	31.9	648	.7878	−.0089	−.0310
	(N.D. du Nord)	26.3	35.2	710	.7730	−.0228	−.0470
	N.D. du Nord	29.2	35.4	602	.7854	−.0209	−.0414
	Guérin	15.8	39.9	975	.7560	−.0220	−.0552
	(Guérin)	15.8	45.7	1065	.7517	−.0265	−.0628
	(Guérin)	15.7	48.6	949	.7680	−.0254	−.0578
	Rivière Solitaire	14.3	54.8	886	.7810	−.0277	−.0578
		14.9	48 01.9	910	.7878	−.0293	−.0603
		15.7	04.7	931	.7935	−.0258	−.0575
		16.0	08.0	904	.8033	−.0234	−.0542
	Arntfield	15.3	12.1	935	.8166	−.0134	−.0452
	Rouyn	01.9	14.4	962	.8275	−.0033	−.0361
	Noranda	01.3	14.9	980	.8276	−.0023	−.0357
	(Evain)	07.2	14.5	946	.8170	−.0155	−.0477
	Lake Fortune	18.0	11.4	937	.8150	−.0137	−.0456
	Kag Lake	28.5	09.2	1106	.7950	−.0145	−.0521

Road Traverse 1947 South of St. L. River between Quebec City and New Brunswick Border — ATLAS

Station No.	Station Name	Longitude ° ′	Latitude ° ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	Beaumont	71 00.7	46 49.6	176	980.7355	−.0421	−.0481
	St. Michel	70 54.7	52.5	32	.7486	−.0470	−.0481
	St. Valier	49.3	53.5	91	.7451	−.0464	−.0495
	Berthier en bas	43.9	55.6	32	.7501	−.0501	−.0512
	Cap St. Ignace	27.7	47 02.2	44	.7538	−.0552	−.0567
	L'Islet	22.4	07.5	31	.7678	−.0504	−.0514
	St. Jean Port Joli	16.4	12.7	49	.7761	−.0482	−.0499
	St. Roch des Aulnaies	11.1	18.5	17	.7904	−.0456	−.0462
	St. Pacôme (Stn.)	69 58.4	24.6	52	.7913	−.0505	−.0523
	St. Philippe de Néri	53.2	27.8	144	.7907	−.0473	−.0522
	St. Pascal	48.3	31.6	182	.7926	−.0475	−.0537
	Ste. Hélène	44.2	35.4	317	.7916	−.0415	−.0523
	St. André (Stn.)	41.4	37.9	347	.7942	−.0399	−.0517
	(St. André)	44.0	40.3	23	.8233	−.0448	−.0456
	N.D. du Portage	37.1	45.8	34	.8318	−.0435	−.0447
	St. Alexandre	38.1	41.1	369	.7989	−.0379	−.0505
	(Provincial Forest)	32.5	36.4	768	.7649	−.0273	−.0534
	Pelletier	25.8	32.8	1260	.7357	−.0048	−.0477
	St. Éleuthère	17.7	29.4	947	.7609	−.0039	−.0362
	(St. Éleuthère)	17.2	30.0	706	.7749	−.0135	−.0375

PRINCIPAL FACTS FOR GRAVITY STATIONS

Road Traverse 1947 South of St. Lawrence River

Station No.	Station Name	Longitude °	Longitude ′	Latitude °	Latitude ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	Estcourt	69	13.5	47	27.5	711	980.7704	−.0138	−.0380
	Sully		10.0		27.4	709	.7689	−.0153	−.0395
	Rivière-Bleue		02.7		26.1	667	.7665	−.0198	−.0425
	Glendyne	68	55.4		23.7	672	.7620	−.0202	−.0431
	Les Étroits		54.2		23.1	673	.7615	−.0197	−.0426
	Boundary Stn.		43.6		22.3	684	.7615	−.0175	−.0408
	Interprovincial Bdy.		29.2		29.3	490	.7861	−.0216	−.0383
	Ste. Rose du Dégelé		39.0		33.0	530	.7866	−.0228	−.0409
	N.D. du Lac		48.0		36.7	604	.7856	−.0225	−.0431
	Cabano		53.0		40.9	563	.7936	−.0246	−.0438
	St. Louis du Ha Ha		59.2		40.0	984	.7719	−.0053	−.0389
	Rivière du Loup	69	31.7		49.6	412	.8141	−.0313	−.0454
	Rivière du Loup		31.7		49.6	301	.8217	−.0342	−.0444
	St. Nicholas	71	23.6	46	42.0	223	.7305	−.0313	−.0389
	St. Antoine		34.0		39.7	162	.7314	−.0327	−.0382
	Ste. Croix		43.8		37.3	218	.7251	−.0301	−.0375
	Lotbinière		56.0		36.9	86	.7404	−.0266	−.0295
	Deschaillons	72	06.1		33.2	151	.7307	−.0247	−.0298
	Ste. Sophie		06.5		25.6	232	.7004	−.0359	−.0439
	Gentilly		16.5		24.0	58	.7167	−.0335	−.0355
	Ste. Angèle de Laval		30.7		19.6	32	.7107	−.0354	−.0365
	Nicolet		36.3		13.5	67	.6923	−.0414	−.0437
	N.D. du Bon Conseil		20.6		00.1	274	.6627	−.0313	−.0407
	St. Albert		05.4		00.1	380	.6835	−.0006	−.0135
	Bon Conseil Stn.		23.4	45	57.6	306	.6584	−.0288	−.0392
	Ste. Rosalie		54.1		38.6	112	.6523	−.0247	−.0285
	St. Mathias	73	16.1		28.4	45	.6470	−.0209	−.0224
	Richelieu		16.0		26.8	85	.6408	−.0209	−.0238
	Dorval		44.4		26.9	83	.6461	.0256	−.0188

Road Traverse—1948 in vicinity of Joliette and St. Michel des Saints

ATLAS

Station No.	Station Name	Longitude °	Longitude ′	Latitude °	Latitude ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	Marelan	74	33.0	45	38.2	256	980.6471	−.0157	−.0244
			16.0		38.0	255	.6455	−.0171	−.0258
	St. Hermas		11.5		36.2	159	.6485	−.0204	−.0259
			06.4		36.9	139	.6476	−.0242	−.0290
		73	59.7		34.9	130	.6488	−.0209	−.0253
	(St. Eustache)		52.8		33.9	92	.6471	−.0246	−.0278
	Rosemere		47.8		38.0	89	.6504	−.0278	−.0309
	St. Maurice		45.5		40.0	89	.6534	−.0278	−.0309
	Terrebonne		37.3		41.8	59	.6599	−.0268	−.0289
	(Charlemagne)		28.3		43.0	42	.6605	−.0296	−.0311
			25.4		45.7	38	.6662	−.0283	−.0296
	St. Norbert Stn.		16.9	46	08.8	170	.6887	−.0282	−.0340
	St. Norbert		19.0		10.2	256	.6838	−.0271	−.0358
			19.9		14.2	667	.6570	−.0213	−.0440
			20.8		15.9	683	.6539	−.0255	−.0487
	St. Gabriel		22.9		17.5	603	.6575	−.0318	−.0523
	St. Damien		28.9		20.0	613	.6527	−.0393	−.0602
			32.5		19.7	742	.6404	−.0391	−.0644
			36.5		19.4	716	.6380	−.0434	−.0678

PRINCIPAL FACTS FOR GRAVITY STATIONS

Road Traverse 1948 | ATLAS

Station No.	Station Name	Longitude ° ′	Latitude ° ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	Ste. Émélie de l'Énergie	73 38.6	46 19.3	744	980.6363	−.0424	−.0678
		40.3	21.3	890	.6301	−.0379	−.0682
	La Barrière	43.0	25.3	1033	.6282	−.0323	−.0675
		43.3	28.2	1316	.6166	−.0216	−.0664
	La Glacière	44.3	29.8	1492	.6134	−.0108	−.0616
		47.0	32.1	1577	.6099	−.0097	−.0634
	St. Michel des Saints	55.0	40.7	1201	.6453	−.0225	−.0634
	(St. Michel des Saints)	55.6	41.1	1214	.6474	−.0198	−.0612
	(St. Michel des Saints)	56.1	41.3	1280	.6436	−.0177	−.0613
	(St. Michel des Saints)	57.0	42.0	1338	.6420	−.0149	−.0605
	(St. Michel des Saints)	57.9	42.5	1377	.6409	−.0131	−.0600
	(St. Michel des Saints)	54.9	41.5	1199	.6465	−.0227	−.0636
	(St. Michel des Saints)	54.3	39.3	1216	.6445	−.0198	−.0612
		51.4	36.3	1313	.6327	−.0180	−.0627
	St. Zénon	49.1	33.6	1571	.6154	−.0070	−.0605
		33.7	17.4	677	.6437	−.0384	−.0615
	St. Jean de Matha	32.1	13.8	759	.6412	−.0278	−.0537
	St. Félix de Valois	25.5	10.3	412	.6678	−.0285	−.0426
		25.2	05.0	199	.6847	−.0238	−.0306
	Joliette	26.0	01.3	193	.6908	−.0126	−.0192
	St. Thomas de Joliette	21.3	00.5	99	.6905	−.0206	−.0240
		18.7	02.7	93	.6901	−.0248	−.0280
		15.0	05.4	75	.6908	−.0299	−.0325
	Berthier	12.7	05.3	34	.6915	−.0329	−.0341
		11.0	03.6	32	.6873	−.0348	−.0359
		11.2	00.5	34	.6838	−.0334	−.0346
	Lanoraie	13.2	45 57.5	45	.6811	−.0306	−.0321
	Lavaltrie	16.7	53.1	70	.6777	−.0250	−.0274
	(L'Assomption)	24.9	50.3	54	.6764	−.0236	−.0255
	Vaucluse	25.7	53.4	71	.6818	−.0212	−.0236
		26.1	57.7	113	.6886	−.0170	−.0208
		26.8	59.1	138	.6890	−.0163	−.0210
	Rawdon	42.9	46 02.7	572	.6469	−.0230	−.0425
	Mount Loyal	48.2	01.8	706	.6259	−.0301	−.0541
	St. Théodore	53.6	04.3	799	.6152	−.0357	−.0630
		59.0	08.0	1124	.5933	−.0327	−.0710
	Notre Dame de la Merci	74 03.4	13.4	1252	.5943	−.0277	−.0704
		08.7	16.0	1327	.5923	−.0266	−.0718
	St. Donat	13.2	19.1	1350	.5934	−.0280	−.0740
		14.4	14.0	1442	.5857	−.0194	−.0685
		15.9	08.0	1236	.5786	−.0368	−.0789
	Ste. Agathe	17.0	03.1	1207	.5861	−.0247	−.0658
	St. Alexis	73 36.9	56.0	219	.6766	−.0164	−.0239
	St. Esprit	39.9	54.1	204	.6752	−.0164	−.0234
	Papineau	74 00.0	44.8	228	.6575	−.0178	−.0256
	Pointe au Chêne	45.0	38.7	187	.6710	−.0010	−.0054
	Buckingham Jct.	75 25.2	32.8	190	.6574	−.0034	−.0099

PRINCIPAL FACTS FOR GRAVITY STATIONS

Rail Traverse 1948 from La Tuque to Cochrane Ont. N.A.85

Station		Longitude		Latitude		Elevation Feet	Observed Gravity	Gravity Anomalies	
No.	Name	°	′	°	′			Free Air	Bouguer
	La Tuque	72	47.0	47	26.3	545	980.7750	−.0230	−.0416
	Stirling		51.4		34.2	596	.7836	−.0214	−.0417
	Cressman		56.5		38.4	601	.7800	−.0309	−.0513
	Rapide Blanc	73	03.0		40.6	879	.7739	−.0141	−.0441
	Lac Darey		09.5		38.9	1032	.7594	−.0117	−.0469
	Duplessis		12.6		42.2	972	.7639	−.0178	−.0509
	Windigo		19.8		46.0	929	.7738	−.0176	−.0493
	Ferguson		25.1		48.7	999	.7730	−.0159	−.0500
	Vandry		33.2		51.4	1030	.7763	−.0137	−.0488
	Weymont		45.3		54.3	1152	.7760	−.0068	−.0461
	Cann		52.9		54.3	1187	.7786	−.0010	−.0414
	Hibbard	74	02.9		52.6	1462	.7596	.0084	−.0414
	Casey		11.0		53.6	1374	.7669	.0059	−.0409
	McCarthy		21.3		52.1	1432	.7616	.0083	−.0405
	Wykes		31.3		53.2	1466	.7632	.0115	−.0384
	Parent		37.0		55.4	1400	.7720	.0108	−.0369
	Timbrell		45.8		58.4	1410	.7795	.0147	−.0333
	Strachan		53.4	48	03.0	1454	.7846	.0171	−.0325
	Greening		59.5		07.0	1424	.7927	.0163	−.0322
	Froissart	75	10.8		06.8	1347	.7971	.0138	−.0321
	Oskelaneo		12.3		06.6	1362	.7950	.0134	−.0330
	Clova		21.8		06.7	1389	.7930	.0138	−.0335
	Coquar		29.2		07.3	1478	.7904	+.0187	−.0316
	Monet		38.8		10.1	1456	.7978	.0199	−.0297
	Bourmont		50.0		12.1	1449	.7992	.0176	−.0318
	Langlade		58.7		13.8	1422	.8004	.0138	−.0347
	Dix	76	06.0		15.3	1385	.8001	.0077	−.0395
	Bolger		18.8		15.1	1315	.7977	−.0010	−.0458
	Forsythe		26.0		14.1	1301	.7891	−.0094	−.0537
	Doucet		34.7		13.5	1220	.7818	−.0234	−.0650
	Press		44.1		14.5	1201	.7817	−.0268	−.0677
	Signal		50.1		17.8	1165	.7943	−.0225	−.0622
	Forget		57.0		19.6	1136	.7999	−.0223	−.0610
	Regiskan	77	04.8		19.8	1099	.8035	−.0225	−.0600
	Phipps		06.8		20.2	1100	.8085	−.0180	−.0555
	Senneterre		14.6		23.6	1027	.8216	−.0169	−.0519
	Belcourt		21.1		24.2	1023	.8326	−.0072	−.0420
	Uniacke		30.8		25.3	1058	.8294	−.0087	−.0447
	Barraute		38.2		26.4	1024	.8297	−.0133	−.0482
	Natagan		41.4		27.3	1074	.8285	−.0111	−.0477
	Fisher		48.2		29.3	1122	.8352	−.0029	−.0411
	Landrienne		57.1		33.3	1051	.8416	−.0091	−.0449
	Amos	78	07.1		34.3	991	.8486	−.0093	−.0430
	La Ferme		11.9		34.6	1049	.8412	−.0116	−.0474
	Villemontel		21.7		37.7	1047	.8528	−.0049	−.0406
	Launay		32.1		38.8	1055	.8344	−.0242	−.0601
	Taschereau		41.6		40.0	1015	.8337	−.0304	−.0650
	Authier		51.4		43.7	1005	.8582	−.0124	−.0466
	Makamik	79	00.5		45.5	933	.8611	−.0189	−.0507
	Colombourg		08.0		46.8	931	.8559	−.0262	−.0579
	La Sarre		12.2		48.0	880	.8561	−.0326	−.0626
	Dupuy		21.7		49.8	943	.8640	−.0215	−.0536

PRINCIPAL FACTS FOR GRAVITY STATIONS

Rail Traverse 1948 from La Tuque to Cochrane, Ont. N.A.85

Station No.	Station Name	Longitude °	Longitude ′	Latitude °	Latitude ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	La Reine	79	30.3	48	52.0	908	980.8533	−.0388	−.0697
	Goodwin		41.4		54.3	943	.8582	−.0340	−.0661
	Eades		52.4		56.4	905	.8799	−.0191	−.0499
	Mace		56.3		56.7	880	.8790	−.0227	−.0527
	Low Bush	80	08.2		55.4	886	.8801	−.0192	−.0493
	Kirke		14.5		55.6	938	.8756	−.0191	−.0510
	Bingle		23.9		56.9	969	.8713	−.0144	−.0554
	Stimson		37.4		58.7	984	.8809	−.0140	−.0476
	Norembega		43.5		59.4	981	.8845	−.0117	−.0451
	Brower		50.1	49	00.8	873	.8903	−.0182	−.0479
	Abitibi		53.5		01.6	892	.8929	−.0150	−.0454
	Cochrane (pend)	81	00.7		03.7	915	.8874	−.0215	−.0526
	Tiblemont	77	18.8	48	18.6	1041	.8214	−.0083	−.0437
	Ballast Pit (M.17)		25.9		11.5	1051	.8097	−.0084	−.0442
	Pascalis		29.1		08.9	1091	.8103	−.0002	−.0373
	Colombière		35.4		05.7	—	.8014	−.	
	Val d'Or		46.4		06.6	1010	.8116	−.0031	−.0375
	Du Buisson		53.9		05.9	985	.8063	−.0097	−.0432
	Malartic	78	07.5		08.3	1042	.8025	−.0117	−.0472
	Heva		13.3		10.8	1064	.8025	−.0133	−.0496
	Cadillac		22.8		13.3	1023	.8032	−.0203	−.0551
	Montanier		30.0		12.8	1097	.7995	−.0162	−.0536
	Bousquet		36.0		12.9	994	.8066	−.0190	−.0529
	Joannes		42.5		13.5	1051	.8013	−.0198	−.0556
	McWatters		54.7		12.9	1001	.8155	−.0094	−.0435
	Noranda-Rouyn (CNR Stn.)	79	01.7		14.8	978	.8267	−.0032	−.0365

Road Traverse 1950 from Quebec City to St. Siméon NA85

Station No.	Station Name	Longitude °	Longitude ′	Latitude °	Latitude ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	Quebec	71	13.2	46	48.2	334	980.7289	−.0318	−.0432
	Dufournel		04.7		55.2	25	.7672	−.0331	−.0339
	Chateau Richer		01.0		58.3	18	.7688	−.0368	−.0374
	Ste Anne de Beaupré	70	55.4	47	01.5	18	.7682	−.0422	−.0428
	St. Joachim		50.8		03.3	25	.7728	−.0397	−.0405
	St. Tite des Caps		46.4		08.5	1041	.7285	−.0038	−.0336
			41.2		15.2	1980	.6913	.0449	−.0225
			36.7		21.7	1215	.7526	.0445	−.0169
	Les Éboulements		19.0		28.8	905	.7622	−.0057	−.0365
	Ruisseau Jureux		12.6		32.3	18	.8216	−.0349	−.0355
	Cap à l'Aigle		07.4		38.4	258	.8267	−.0164	−.0252
	Rivière au Saumon		58.2		45.2	841	.8054	.0069	−.0217
	St. Siméon		52.7		50.7	41	.8584	−.0236	−.0250

PRINCIPAL FACTS FOR GRAVITY STATIONS

Air Trip—1951 WORDEN No. 44.

Station No.	Station Name	Longitude °	Longitude ′	Latitude °	Latitude ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	South Porcupine (Air Base)	81	11.8	48	28.6	920	980.8342	−.0219	−.0532
	Deception Lake		18.1	49	01.6	898	.8982	−.0091	−.0397
			13.3		23.0	747	.9427	−.0107	−.0362
	McInnes (Air Base)		21.2		32.3	717	.9690	−.0011	−.0255
		80	28.5		50.2	925	.9903	.0132	−.0183
		81	41.0		40.3	741	.9885	.0088	−.0164
	Nonigose Lake		55.3		48.9	692	981.0081	.0110	−.0126
	Smoky Falls	82	09.8	50	03.1	564	.0382	.0080	−.0112
	Guilfoyle Lake		22.4	49	45.3	705	980.9869	−.0036	−.0276
			09.7		35.2	698	.9900	.0139	−.0099
		81	49.9		21.8	732	.9531	.0001	−.0249
	Tahquatagama Lake		22.5		50.5	807	981.0056	.0169	−.0106
		80	59.3		47.7	851	980.9970	.0166	−.0123
	Harris Lake		48.3		35.3	831	.9690	.0052	−.0231
			38.1		55.6	859	981.0056	.0143	−.0150
	Stringer Lake		52.2	50	11.6	746	.0332	.0076	−.0178
	Agaskagou Lake		24.0		13.9	839	.0221	.0018	−.0268
		79	58.1		11.8	876	.0063	−.0074	−.0372
			34.4		16.7	836	.0091	−.0157	−.0441
			12.8		08.8	816	980.9778	−.0371	−.0649
			17.8	49	53.1	799	.9892	−.0040	−.0313
			41.8		59.3	858	.9919	−.0050	−.0342
		80	00.0		54.6	873	.9695	−.0190	−.0487
			19.4		37.5	1004	.9450	−.0058	−.0400
	Chabbie Lake	79	44.8		34.6	938	.9375	−.0152	−.0471
	Bateman Lake	80	03.5		23.7	986	.9105	−.0215	−.0550
	Little Abitibi Lake		31.8		24.8	863	.9338	−.0114	−.0408
			55.0		27.1	862	.9472	−.0015	−.0309
	Lillabella Lake	81	01.4		06.5	818	.8997	−.0225	−.0503
	Cochrane Court House		02.0		03.6	—	—	—	—
		80	41.7		13.2	906	.9162	−.0077	−.0385
			04.1		11.3	1031	.8881	−.0212	−.0563
	Joe Lake	79	32.0		05.2	1001	.8741	−.0289	−.0630
	Turgeon Lake		02.5		01.5	960	.8763	−.0251	−.0578
			00.8		10.8	1073	.8744	−.0302	−.0667
	Mistawak Lake	78	40.3		25.2	882	.9108	−.0342	−.0643
		79	06.8		35.8	857	.9476	−.0145	−.0437
		78	54.0		47.0	832	.9587	−.0224	−.0508
	Taschereau (Air Base)		40.9	48	40.0	1005	.8338	−.0313	−.0655
			17.0	49	52.0	801	.9738	−.0177	−.0449
	Mattagami Lake	77	47.0		53.9	818	.9540	−.0387	−.0665
			56.0		37.7	821	.9428	−.0255	−.0534
	Harricanaw River	78	17.8		27.3	882	.9292	−.0179	−.0480
			25.0		14.6	938	.8965	−.0265	−.0584
			41.1		03.1	996	.8779	−.0224	−.0563
	Chicobi Lake		30.1	48	51.5	978	.8638	−.0209	−.0542
	Obalski Lake	77	57.4		46.5	958	.8687	−.0105	−.0431
	Fiedmont Lake		40.9		20.5	992	.7975	−.0397	−.0735
	Guequen Lake		12.3		08.0	1047	.7969	−.0056	−.0413
	Senneterre (Air Base)		13.6		23.4	1008	.8222	−.0178	−.0521
	Sabourin Lake		42.6	47	56.2	1082	.7754	−.0169	−.0538
	Mourier Lake	78	10.0		59.5	995	.7829	−.0225	−.0564

PRINCIPAL FACTS FOR GRAVITY STATIONS

Air Trip—1951 | WORDEN No. 44.

Station No.	Station Name	Longitude °	Longitude '	Latitude °	Latitude '	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	Clerion Lake	78	40.9	47	49.8	898	980.7708	−.0292	−.0598
	Beaumesnil Lake	79	03.8		46.4	884	.7710	−.0253	−.0554
	Lac des Quinze		03.9		29.2	862	.7556	−.0169	−.0463
	Guay Lake		01.2		11.9	895	.7219	−.0217	−.0521
	Lac aux Sables	78	42.1		22.5	1026	.7562	.0091	−.0258
	L. Simard		35.8		35.7	868	.7610	−.0208	−.0503
	Bay Lake		18.0		25.3	1084	.7297	−.0161	−.0531
	L. Decelles (Reservoir)		03.0		41.1	1027	.7561	−.0188	−.0538
	Gaotanaga Lake	77	35.8		38.2	1052	.7560	−.0121	−.0480
	L. Denain	76	59.0		54.0	1238	.7699	−.0045	−.0466
	L. Tavernier		59.5	48	11.3	1098	.8086	−.0048	−.0422
	Waswanipi Lake		39.6	49	28.7	877	.9162	−.0335	−.0634
	L. Baptiste		59.2		32.2	1139	.8976	−.0327	−.0715
	Bell River	77	15.7		23.5	899	.9003	−.0395	−.0702
	Taibi Lake		34.0		26.9	901	.9019	−.0429	−.0735
			44.1	48	53.8	1085	.8398	−.0383	−.0753
	L. Despinassy		18.1		46.7	992	.8687	−.0076	−.0414
	Martin Lake	76	48.5		26.7	1383	.7890	−.0206	−.0677
	L. Faillon		44.5		19.0	1164	.7891	−.0297	−.0693
	L. Valmy		13.6		26.2	1272	.8127	.0083	.0350
	L. Megiscane	75	52.0		36.1	1273	.8230	−.0111	−.0544
	L. St. Cyr		38.7		48.9	1279	.8312	−.0214	−.0650
	L. Lacroix		22.0	49	01.4	1264	.8605	−.0121	−.0552
			39.6		12.9	1292	.8454	−.0417	−.0857
			55.8		04.6	1273	.8518	−.0248	−.0681
	Wilson Lake	76	28.0		07.9	1213	.8657	−.0214	−.0626
	Wetethagami Lake		14.0	48	55.8	1205	.8422	−.0277	−.0690
	L. Cuvillier		33.6		53.9	1233	.8405	−.0238	−.0658
	L. Charette		22.3		38.6	1242	.8227	−.0180	−.0603
			46.1		39.5	1284	.8160	−.0140	−.0658
	L. Parent	77	04.4		36.0	994	.8385	−.0217	−.0555
	L. Parent	76	56.9		45.4	994	.8481	−.0260	−.0599
	L. Quevillon	77	00.9	49	05.9	828	.8927	−.0276	−.0558
	Wedding Lake	76	43.5		17.9	995	.9108	−.0117	−.0456
	Pustkitamika Lake		18.2		24.3	954	.9087	−.0272	−.0597
	L. au Goeland		45.5		43.7	862	.9311	−.0423	−.0717
	L. Bouchier	77	48.3	50	08.0	803	.9702	−.0448	−.0721
		78	11.8		10.2	813	.9787	−.0386	−.0663
	Soscumica Lake	77	30.2		17.4	802	.9926	−.0364	−.0637
	Mattagami Lake		28.2		02.2	818	.9577	−.0470	−.0748
	Waswanipi Post (Air Base)	76	30.0	49	39.3	882	.9095	−.0554	−.0855
	Lady Beatrix Lake	77	03.0	50	02.5	891	.9635	−.0350	−.0653
	Olga Lake		10.0	49	49.9	841	.9596	−.0250	−.0536
	Bachelor Lake	76	07.4		31.0	977	.9224	−.0213	−.0581
		75	52.6		47.1	1010	.9522	−.0123	−.0467
	Caupichigau Lake		36.1	50	04.3	1114	.9607	−.0195	−.0575
	L. Manson		51.3		14.2	1076	.9873	−.0112	−.0478
	Kaminskanun Lake.	76	01.6		28.5	1112	981.0048	−.0114	−.0493
			13.0		41.7	879	.0443	−.0133	−.0433
	Kenonisca Lake		33.0		34.6	864	.0266	−.0220	−.0515
	Opatawaga Lake		41.2		22.0	891	980.9975	−.0299	−.0602
			18.5		15.2	982	.9850	−.0238	−.0573

PRINCIPAL FACTS FOR GRAVITY STATIONS

Air Trip—1951 WORDEN No. 44.

Station No.	Station Name	Longitude °	Longitude ′	Latitude °	Latitude ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	Yapuwichi Lake	76	17.6	50	02.2	939	980.9621	−.0315	−.0635
	Maicasagi Lake		41.0	49	55.3	862	.9582	−.0324	−.0618
	Lady Beatrix Lake		52.5	50	12.2	891	981.0144	.0015	−.0288
	Crow Bay		41.9		51.2	800	.0611	−.0181	−.0453
			47.3	51	05.7	758	.0838	−.0206	−.0464
	Lake Evans	77	03.9	50	57.9	800	.0630	−.0260	−.0532
	Chabinoche Lake.		04.7		29.6	913	.0041	−.0325	−.0352
	Lac Maurice		56.2		27.1	807	.0160	−.0269	−.0544
	L. Lucie	78	24.5		24.2	789	.0102	−.0301	−.0570
			18.6		35.7	758	.0326	−.0276	−.0534
			10.0		49.7	651	.0624	−.0285	−.0506
	L. Pirie	77	44.1		51.3	833	.0519	−.0242	−.0526
	L. du Tust		20.6	51	01.6	807	.0726	−.0212	−.0487
	L. Colomb		38.3		03.8	757	.0865	−.0152	−.0410
			07.2		12.0	739	.0955	−.0200	−.0452
	Nemiscau (Air Base)	76	54.0		19.4	766	.1026	−.0213	−.0473
	L. Dana	77	17.3	50	45.9	800	.0340	−.0373	−.0645
	L. Randal		19.8	51	21.3	783	.1079	−.0172	−.0438
			34.5		33.0	619	.1409	−.0167	−.0378
			50.8		43.4	539	.1699	−.0105	−.0289
			46.9		59.7	551	.1884	−.0147	−.0334
	Mirabelli Lake		22.6		51.6	611	.1610	−.0246	−.0454
			02.5		58.9	730	.1584	−.0267	−.0516
		76	47.8		44.8	652	.1382	−.0336	−.0558
		77	12.0		35.2	688	.1270	−.0274	−.0508
	Lacs Jolliet	76	49.3		33.7	706	.1170	−.0335	−.0575
			28.8		30.1	761	.1136	−.0264	−.0523
	L. Champion		13.7		41.6	742	.1213	−.0373	−.0626
		75	53.4		54.1	993	.1260	−.0273	−.0611
			24.4		54.2	936	.1365	−.0224	−.0542
	L. Le Vilin	74	58.0		42.1	1007	.1120	−.0225	−.0568
	L. Lemare	75	25.0		43.0	934	.1210	−.0216	−.0535
			48.4		28.6	764	.1084	−.0291	−.0552
		76	08.8		21.3	831	.1004	−.0201	−.0484
	L. Poncet		02.5		06.1	872	.0827	−.0136	−.0433
			29.9		07.0	874	.0833	−.0121	−.0419
	Mishagomish Lake		12.1	50	51.7	921	.0564	−.0121	−.0434
		75	50.0		35.5	1109	.0240	−.0029	−.0407
	Waposite Lake		18.6		14.7	1178	980.9800	−.0096	−.0497
	L. Lamarck		18.2	49	55.4	1103	.9587	−.0094	−.0469
	Opemisca Lake	74	48.2		54.2	1176	.9508	−.0086	−.0486
	L. Cache (Chibougamau Air Base)		25.4		49.8	1245	.9440	−.0024	−.0448
			49.8	50	01.1	1180	.9616	−.0077	−.0479
		75	07.5		04.5	1160	.9740	−.0022	−.0417
	Opataca Lake	74	55.4		23.7	1180	.9882	−.0145	−.0547
	Assinica Lake	75	15.9		32.0	1178	981.0097	−.0055	−.0456
			29.8		40.5	1046	.0334	−.0072	−.0424
	Thin Man Lake		36.0		53.0	1064	.0553	−.0016	−.0379
	L. Lecordier		37.5	51	07.7	988	.0764	−.0094	−.0430
	L. Villon		14.9		06.3	1010	.0652	−.0164	−.0508
	L. Montmort	74	50.7		09.0	1074	.0655	−.0141	−.0507

PRINCIPAL FACTS FOR GRAVITY STATIONS

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Station		Longitude		Latitude		Elevation Feet	Observed Gravity	Gravity Anomalies	
No.	Name							Free Air	Bouguer
		°	′	°	′				
		75	09.2	50	54.2	1096	981.0526	−.0031	−.0404
		74	47.5		45.9	1223	.0338	.0023	−.0393
			33.0		29.8	1243	980.9932	−.0127	−.0550
	L. Lemieux		32.3		18.9	1245	.9808	−.0087	−.0511
	L. Chevrillon		27.2		01.1	1205	.9593	−.0077	−.0487
	Waconichi Lake		04.0		06.9	1267	.9640	−.0057	−.0489
	Mistassini Lake		01.0		32.7	1220	981.0016	−.0107	−.0523
	Mistassini Post	73	52.8		24.6	1230	980.9835	−.0156	−.0578
		74	13.0		56.1	1229	981.0266	−.0194	−.0613
		73	46.6	51	08.9	1211	.0527	−.0138	−.0550
	Mistassini Lake		05.0		21.9	1220	.0569	−.0278	−.0694
	Mistassini Lake	72	59.2		16.6	1220	.0510	−.0260	−.0676
	Albanel Lake		50.7		11.0	1265	.0356	−.0289	−.0720
	Albanel Lake	73	13.3	50	57.0	1265	.0290	−.0149	−.0580
	Mistassini Lake		29.2	51	02.8	1220	.0411	−.0155	−.0571
			54.4	50	51.4	1235	.0287	−.0098	−.0519
	Mistassini Lake		43.0		50.1	1220	.0293	−.0086	−.0502
	Albanel Lake		30.8		45.1	1265	.0204	−.0060	−.0491
	St. Félicien (AirBase)	72	26.5	48	39.0	350	980.8673	−.0599	−.0698
	File-axe Lake	73	34.8	50	18.9	1480	.9551	−.0123	−.0627
	L. Laganiere		39.6		05.1	1332	.9350	−.0259	−.0713
			52.0	49	55.1	1481	.9178	−.0143	−.0647
			25.4		54.6	1333	.9329	−.0123	−.0577
			10.7	50	11.2	1273	.9558	−.0197	−.0630
		72	56.5		28.4	1543	.9564	−.0192	−.0717
			36.0		19.7	1427	.9504	−.0232	−.0718
	Swan Lake		53.3	49	53.1	1356	.9246	−.0163	−.0624
		73	19.4		46.4	1354	.9158	−.0156	−.0618
			50.2		37.7	1378	.8917	−.0242	−.0711
	L. Presqu'ile	74	50.1		44.1	1165	.9372	−.0082	−.0479
	Dickson Lake	75	12.5		38.7	1134	.9082	−.0321	−.0708
			32.1		35.1	1018	.9174	−.0285	−.0632
			50.0		22.3	1122	.8854	−.0317	−.0699
			18.8		27.5	1190	.9018	−.0243	−.0621
	L. Hébert		15.4		16.2	1278	.8626	−.0308	−.0743
		74	38.0		13.1	1445	.8365	−.0365	−.0857
	Surprise Lake		55.6		21.3	1223	.8813	−.0249	−.0665
	Iréné Lake		46.2		32.2	1195	.9205	−.0045	−.0452
			02.7		31.9	1303	.8890	−.0253	−.0697
		73	42.5		27.6	1240	.8885	−.0254	−.0676
			25.6		30.8	1382	.8994	−.0059	−.0530
			03.5		23.4	1141	.8802	−.0368	−.0756
	Petit L. Chigoubiche		32.9		12.7	1167	.8635	−.0350	−.0748
			45.9		01.1	1332	.8318	−.0340	−.0794
	Potrincourt Lake	74	07.4		10.8	1280	.8606	−.0245	−.0681
	Rohault Lake		20.8		25.0	1283	.8892	−.0168	−.0605
	Obatogamau Lake		27.4		38.6	1218	.9100	−.0223	−.0638
	L. Magouche	72	15.5	48	58.7	642	.8693	−.0578	−.0797
	L. Damville	73	05.3	49	08.4	925	.8642	−.0507	−.0822
		72	34.9		20.4	782	.8968	−.0495	−.0761
	L. Clair		08.8		32.0	674	.9151	−.0586	−.0816
			10.3		48.0	1433	.9076	−.0184	−.0672

PRINCIPAL FACTS FOR GRAVITY STATIONS

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Station No.	Station Name	Longitude ° ′	Latitude ° ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	L. Goéland	71 40.5	49 46.7	1290	980.9133	−.0243	−.0728
	L. Margane	08.0	55.4	1309	.9487	−.0000	−.0446
	L. à Paul	70 45.2	50.9	1335	.9499	.9104	−.0351
	Shipshaw Lake	51.4	34.9	1289	.9127	−.0075	−.0514
	Etienniche Lake	71 21.3	30.0	1040	.9112	−.0251	−.0605
		27.0	15.3	870	.8813	−.0491	−.0787
	Connelly Lake	58.0	20.3	670	.9038	−.0529	−.0757
	L. de l'Ouest	56.1	06.4	673	.8942	−.0415	−.0644
		72 14.1	09.1	628	.8945	−.0494	−.0708
	L. Bernabé	71 38.0	48 54.1	683	.8630	−.0534	−.0766
	L. Vermont	09.0	56.0	1009	.8517	−.0369	−.0713
		70 56.5	49 12.2	1766	.8453	.0038	−.0563
	Lac à la Croix Camp	41.0	21.2	1676	.8667	.0033	−.0537
	Pipmuacan Lake	25.3	30.9	1225	.9023	−.0179	−.0596
	Itamamo Lake	28.2	09.9	1565	.8603	.0037	−.0496
	L. Beauséjour	44.9	48 57.9	2137	.7958	.0105	−.0623
	L. Poulin-de-Courval	27.9	52.9	2207	.8005	.0105	−.0579
		20.6	56.0	1848	.8159	.0062	−.0567
		35.3	38.0	2169	.7711	.0185	−.0554
	L. Brébeuf	36.0	11.9	758	.8257	−.0206	−.0464
		71 14.5	12.0	1139	.7894	−.0212	−.0600
	L. à la Carpe	51.7	12.6	1156	.7914	−.0185	−.0578
	L. à la Croix	72 51.9	36.9	1420	.7982	−.0232	−.0716
		73 18.0	18.4	1567	.7675	−.0124	−.0658
	L. de la Fourche	07.0	05.6	1130	.7842	−.0177	−.0562
		01.0	47 52.4	909	.7850	−.0179	−.0489
	L. Chaumonot	72 48.1	58.8	992	.7897	−.0150	−.0488
	L. Panache	33.5	48 16.9	1171	.7960	−.0190	−.0589
		27.0	47 53.9	1170	.7831	.0026	−.0373
	L. Édouard	21.6	36.3	1163	.7760	.0211	−.0185
	L. des Isles	22.5	13.6	1016	.7661	.0315	−.0032
	L. à Beauce (Air Base)	45.9	19.0	689	.7650	−.0085	−.0320
	Mekinac Lake	41.8	03.7	515	.7538	−.0132	−.0307
	Brown Lake	73 10.9	46 55.9	1133	.6861	−.0110	−.0496
	Shawinigan Lake	07.5	40.1	1046	.6693	−.0122	−.0478
	Gd. L. des Isles	30.6	42.8	1275	.6431	−.0210	−.0644
	L. Toro (Resevoir)	46.7	48.4	1175	.6612	−.0207	−.0607
	L. Cypres	74 12.9	31.6	1367	.6177	−.0209	−.0675
	L. Jamet	30.8	33.9	1480	.6093	−.0221	−.0725
	L. Mattawin	16.8	49.2	1621	.6309	−.0102	−.0654
	Clear Lake	73 50.1	47 03.7	1297	.6849	−.0085	−.0527
	L. à la Chienne	31.0	01.8	1347	.6801	−.0057	−.0516
	L. Geoffrion	17.1	14.7	1344	.7087	.0032	−.0426
	L. aux Rats	09.1	29.1	785	.7578	−.0219	−.0486
	Oscar Lake	29.5	32.7	1385	.7240	−.0046	−.0518
	L. Dupuis	46.7	22.9	1219	.7140	−.0155	−.0571
	L. Troyes	74 11.7	11.3	1487	.6809	−.0060	−.0567
	Mazanaskwa Lake	31.6	07.4	1457	.6754	−.0085	−.0581
	L. Maison de Pierre	42.0	46 52.9	1415	.6555	−.0106	−.0588
	Sprouk Lake	46.0	47 13.9	1307	.6955	−.0123	−.0568
	Nemikachi Lake	31.2	24.5	1396	.6994	−.0159	−.0634
	Kempt Lake	11.7	23.2	1371	.7011	−.0145	−.0612

PRINCIPAL FACTS FOR GRAVITY STATIONS

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Station		Longitude	Latitude	Elevation Feet	Observed Gravity	Gravity Anomalies	
No.	Name					Free Air	Bouguer
		° ′	° ′				
	Manuan Lake	74 05.6	47 33.8	1338	980.7290	−.0056	−.0512
	L. Albert	73 31.7	45.8	1162	.7602	−.0090	−.0486
		13.2	44.3	909	.7683	−.0225	−.0535
	L. du Droit	35.5	48 06.4	1666	.7587	−.0060	−.0507
	Ellwood Lake	74 08.9	04.6	1560	.7732	−.0132	−.0399
	L. Lorette	31.1	03.7	1533	.7790	.0179	−.0343
	L. Dugré	48.7	09.8	1569	.7884	.0216	−.0318
	Chapman Lake	40.4	20.4	1235	.7940	−.0201	−.0622
	Great Beaver Lake	20.3	11.2	1403	.7898	.0053	−.0425
		73 53.6	17.7	1277	.7985	−.0077	−.0512
		22.5	27.3	1795	.7636	−.0082	−.0693
		25.0	40.2	1692	.7788	−.0220	−.0796
	L. Lobruère	42.2	29.9	1635	.7793	−.0114	−.0671
		59.2	41.7	1373	.8052	−.0278	−.0745
	Oskelaneo (Air Base)	75 12.0	06.5	1336	.7948	.0090	−.0345
	L. Déziel	74 24.3	34.4	1318	.8025	−.0247	−.0696
	B. de l'Est	75 03.1	21.3	1318	.8027	−.0049	−.0498
	L. Medora	34.3	12.7	1404	.8016	.0149	−.0330
	Pascagama Lake	39.6	30.3	1277	.8206	−.0044	−.0479
	B. Mattawa	22.2	22.9	1318	.8127	.0027	−.0422
		07.0	38.6	1318	.8229	−.0106	−.0555
	Pascagama R.	23.8	46.4	1299	.8279	−.0190	−.0633
		74 51.8	49 01.4	1524	.8287	−.0195	−.0714
		29.3	04.3	1343	.8516	−.0179	−.0636
		16.3	00.5	1364	.8366	−.0253	−.0718
	B. Verreau	33.7	48 48.5	1318	.8239	−.0244	−.0693
	L. Marmette	49.0	38.8	1318	.8064	−.0274	−.0723
	L. Dix-Milles	48.5	47 51.1	1406	.7670	.0127	−.0351
	L. Dandurand	29.6	48.5	1403	.7587	.0081	−.0397
	Wagwabika Lake	38.2	36.3	1498	.7246	.0012	−.0498
	Mitchinamekus Lake	75 04.3	18.6	1272	.7091	−.0090	−.0523
	Long Lake	18.0	05.0	861	.7199	−.0164	−.0457
		43.1	00.6	755	.7146	−.0251	−.0508
	Nutakim Lake	36.3	20.5	1313	.7116	−.0055	−.0502
		16.7	27.3	1213	.7294	−.0073	−.0486
	L. Bolduc	21.0	46.7	1402	.7509	.0029	−.0449
		41.3	48 04.0	1438	.7876	.0171	−.0319
	L. Capitachouane	58.4	03.0	1406	.7926	.0205	−.0273
	L. Durand	76 11.1	16.1	1325	.8031	.0038	−.0413
		28.2	47 59.5	1319	.7953	.0204	−.0246
	L. Bouchette	33.5	39.0	1182	.7679	.0108	−.0295
		25.4	24.2	1202	.7279	−.0051	−.0461
	O'Sullivan Lake	01.4	36.0	1308	.7301	−.0107	−.0552
	Eskwahani Lake	75 41.1	48.6	1338	.7539	−.0029	−.0485
	McLennan Lake	46.6	26.1	1380	.7184	−.0008	−.0478
	Poigan Lake	76 18.9	12.0	1079	.7123	−.0140	−.0508
		32.5	02.2	1199	.6873	−.0130	−.0539
	L. Andov	46.2	23.3	1198	.7277	−.0044	−.0452
	Gull Lake	48.6	33.7	1140	.7483	−.0049	−.0437
		77 20.9	37.8	1067	.7606	−.0055	−.0419
		33.9	28.1	1066	.7489	−.0028	−.0391
	Kokomis Lake	58.5	21.3	1100	.7337	−.0046	−.0421

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Station No.	Station Name	Longitude °	Longitude ′	Latitude °	Latitude ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	L. Babinet	78	15.4	47	14.9	1180	980.7174	−.0038	−.0440
	Saseginaga Lake		36.6		07.5	1038	.7156	−.0079	−.0432
	Cataboningue Lake		48.9		02.1	891	.7142	−.0150	−.0453
	Kipawa Lake	79	10.9	46	59.6	884	.7093	−.0168	−.0469
		78	46.3		49.3	884	.6899	−.0208	−.0509
	L. Sairs		26.5		50.5	892	.6893	−.0224	−.0528
	Watson Lake		15.0	47	01.2	992	.7001	−.0182	−.0520
	L. Tremblay	77	57.5		08.7	1011	.7121	−.0157	−.0502
	L. des Baies		40.8		16.6	1069	.7228	−.0095	−.0466
	L. Nollet		16.0		16.4	1123	.7214	−.0074	−.0456
			02.6		20.2	1139	.7250	−.0080	−.0468
	L. Nizard	76	53.8		07.5	1198	.6930	−.0154	−.0562
	L. Brulé	77	14.1	46	57.0	1168	.6834	−.0120	−.0518
	Busted Lake		35.1	47	02.8	1181	.6966	−.0063	−.0465
	L. Dumoine		53.6	46	54.7	1030	.6875	−.0175	−.0526
	L. Pin-Blanc	78	09.3		43.1	1093	.6690	−.0126	−.0498
	L. Bleu		23.0		35.2	1063	.6589	−.0137	−.0499
	Nemewin Lake		43.0		27.3	817	.6546	−.0293	−.0571
			10.5		25.2	1112	.6396	−.0133	−.0512
	Russell Lake	77	54.6		37.7	1108	.6645	−.0076	−.0453
	Les Lacs Aumand		32.2		32.5	1185	.6516	−.0054	−.0458
	Bruce Lake		17.8		43.8	1166	.6625	−.0133	−.0530
	Gale Lake	76	50.9		45.1	1184	.6692	−.0068	−.0472
	L. Savary		25.5		43.6	789	.6899	−.0211	−.0480
	Brodtkorb Lake		38.5		31.0	1062	.6659	−.0005	−.0368
	Bryson Lake	77	01.1		29.1	883	.6637	−.0166	−.0467
	St. Patrick Lake		22.4		22.3	886	.6546	−.0153	−.0454
	L. du Princeau		41.1		18.2	690	.6603	−.0218	−.0453
	L. aux Vers		08.1		08.8	860	.6441	−.0079	−.0378
	Usborne Lake	76	40.3		12.7	821	.6629	.0013	−.0266
	L. Mer-Bleue		13.9		14.5	708	.6739	−.0010	−.0251
	L. Bras-Coupé		11.5		33.8	759	.6882	−.0109	−.0368
			05.3		59.3	1094	.6914	−.0145	−.0518
	Ottawa Laurentian Air Service	75	40.7	45	27.4	190	.6353	−.0174	−.0239
	Madawaska Lake	78	24.0		17.7	1401	.5294	−.0052	−.0425
	O'Connell Lodge (Air Base)	76	32.0	47	02.4	1201	.6873	−.0131	−.0540

Primary Bases 1952 Network in Quebec N.A. 85.

Station No.	Station Name	Longitude °	Longitude ′	Latitude °	Latitude ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	St. Anne de Bellevue	73	56.6	45	24.5	110	980.6463	−.0091	−.0133
	Dorval Airport		45.5		27.3	97	.6454	−.0159	−.0192
	Montreal		34.0		30.0	151	.6499	−.0104	−.0155
	Pointe aux Trembles		29.5		38.4	42	.6581	−.0250	−.0265
	St. Sulpice		21.2		49.6	35	.6786	−.0221	−.0233
	Berthierville		10.7	46	05.0	29	.6880	−.0365	−.0375
	Trois Rivières	72	32.3		20.6	49	.7110	−.0350	−.0367
	Cap de la Madeleine		30.0		22.4	55	.7145	−.0336	−.0355
	Ste. Anne de la Pérade		12.2		34.6	38	.7428	−.0223	−.0266
	Portneuf	71	53.0		41.7	19	.7530	−.0275	−.0282

PRINCIPAL FACTS FOR GRAVITY STATIONS

Primary Bases 1952 Network in Quebec — N.A. 85.

Station No.	Station Name	Longitude °	Longitude ′	Latitude °	Latitude ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	Quebec	71	13.2	46	48.2	340	980.7289	−.0312	−.0428
	Lévis		11.0		48.8	17	.7486	−.0428	−.0434
	Montmagny	70	33.1		58.8	51	.7487	−.0545	−.0562
	Ste. Anne de la Pocatière		01.4	47	22.1	154	.7818	−.0467	−.0520
	Notre Dame du Portage	69	37.1		45.8	34	.8318	−.0435	−.0447
	Rivière du Loup		31.7		49.6	290	.8232	−.0337	−.0436
	St. Siméon		53.0		50.7	25	.8584	−.0241	−.0250
	Tadoussac		42.7	48	08.2	10	.8816	−.0296	−.0299
	Petit Saguenay	70	04.2		12.9	58	.8804	−.0332	−.0352
	Grande Baie		51.0		19.1	18	.8713	−.0554	−.5060
	Chicoutimi	71	03.8		25.7	75	.8648	−.0663	−.0689
	Grand Mère	72	41.2	46	36.9	426	.7191	−.0159	−.0304
	St. Tite		33.9		43.4	457	.7316	−.0103	−.0259
	St. Roch de Mékinac		46.3		48.9	478	.7257	−.0224	−.0387
	Rivière aux Rats		53.6	47	12.6	393	.7585	−.0332	−.0466
	Lac à Beauce		46.0		19.3	689	.7650	−.0085	−.0320
	La Tuque		47.0		26.3	545	.7750	−.0230	−.0416
	Lachute	74	20.0	45	39.4	226	.6470	−.0204	−.0281
	St. Jérome		00.2		46.8	310	.6609	−.0097	−.0203
	St. Jacques	73	34.3		56.9	196	.6797	−.0169	−.0235
	Joliette		26.2	46	01.3	186	.6906	−.0135	−.0198
	Stoneham	71	23.5		57.6	511	.7518	−.0063	−.0237
	St. Joseph d'Alma		39.4	48	33.0	302	.8650	−.0557	−.0660
	Roberval	72	12.6		30.7	346	.8587	−.0545	−.0662
	St. Félicien		26.4		39.0	367	.8658	−.0579	−.0704
	Arntfield	79	15.3		12.1	935	.8166	−.0134	−.0452
	Rouyn		01.9		14.4	962	.8275	−.0033	−.0361
	Cache Lake	74	25.6	49	49.6	1245	.9440	−.0024	−.0448
	Rupert House	78	45.1	51	29.2	18	981.1763	−.0326	−.0332
	Nemiscau	76	54.0		19.4	766	.1026	−.0213	−.0473

Road Traverse 1952 La Tuque to St. Roch de Mékinac — N.A. 85.

Station No.	Station Name	Longitude °	Longitude ′	Latitude °	Latitude ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
		72	46.4	47	29.1	505	980.7823	−.0237	−.0409
			43.5		33.3	513	.7858	−.0257	−.0432
			43.9		37.4	526	.7899	−.0265	−.0444
			46.7		27.7	509	.7792	−.0243	−.0417
			47.2		24.4	551	.7747	−.0199	−.0386
			47.0		22.2	531	.7773	−.0162	−.0342
			47.8		20.7	437	.7743	−.0255	−.0404
			50.1		18.1	431	.7742	−.0223	−.0369
			51.6		16.5	445	.7698	−.0229	−.0381
			50.7		14.7	412	.7692	−.0239	−.0380
			53.0		10.4	405	.7585	−.0288	−.0426
			54.4		07.2	431	.7534	−.0267	−.0413
			55.6		05.2	421	.7520	−.0260	−.0403
			55.6		02.9	403	.7472	−.0291	−.0428
			55.7		00.5	450	.7416	−.0267	−.0420
			54.3	46	55.7	390	.7403	−.0264	−.0397
			54.6		52.2	423	.7326	−.0257	−.0401
			48.5		51.6	360	.7383	−.0250	−.0373

PRINCIPAL FACTS FOR GRAVITY STATIONS

Road Traverse 1952 Chibougamau Rd. N.A. 85.

Station		Longitude		Latitude		Elevation Feet	Observed Gravity	Gravity Anomalies	
No.	Name	°	'	°	'			Free Air	Bouguer
		73	12.7	48	56.5	1070	980.9375	−.0461	−.0825
			22.7	49	02.9	1208	.8432	−.0369	−.0780
			41.7		12.5	1267	.8563	−.0382	−.0757
			33.2		07.6	1219	.8478	−.0382	−.0798

Road Traverse 1952 Chicoutimi to Stoneham N.A. 85.

No.	Name	Longitude °	'	Latitude °	'	Elevation Feet	Observed Gravity	Free Air	Bouguer
		71	04.3	48	23.6	438	980.8410	−.0529	−.0678
			06.0		22.1	507	.8370	−.0481	−.0654
			07.9		19.1	487	.8402	−.0424	−.0590
			10.0		17.5	785	.8164	−.0358	−.0625
			13.8		16.3	928	.8048	−.0321	−.0637
			15.9		12.8	1169	.7881	−.0208	−.0607
			14.2		08.3	1407	.7741	−.0058	−.0537
			15.0		05.9	1571	.7622	−.0014	−.0521
			15.1		05.2	1635	.7558	.0020	−.0537
			13.5		01.8	2231	.7194	.0267	−.0492
			14.2	47	59.2	2275	.7122	.0276	−.0499
			14.1		56.9	2479	.7032	.0413	−.0432
			15.2		55.9	2443	.7040	.0402	−.0430
			15.7		52.9	2516	.6950	.0426	−.0431
			15.1		49.1	2499	.6906	.0422	−.0430
			13.2		46.4	2529	.6889	.0474	−.0388
			12.7		43.4	2519	.6894	.0514	−.0344
			13.1		41.0	2457	.6888	.0486	−.0351
			14.2		38.0	2605	.6757	.0539	−.0348
			14.0		34.0	2578	.6731	.0548	−.0330
			14.0		31.1	2554	.6795	.0632	−.0238
			13.9		27.8	2566	.6800	.0699	−.0175
			11.4		24.2	2516	.6749	.0655	−.0202
			13.2		16.1	2309	.6742	.0574	−.0213
			13.3		13.9	2303	.6748	.0607	−.0177
			14.7		10.7	1929	.6910	.0465	−.0192
			14.9		10.2	1929	.6893	.0465	−.0201
			19.3		08.0	1396	.7212	.0307	−.0168
			20.6		06.2	1105	.7371	.0219	−.0157
			21.0		03.4	888	.7389	.0075	−.0227
			21.9	46	59.0	571	.7525	−.0021	−.0215

Road Traverse 1953 St. Urbain area N.A. 85

No.	Name	Longitude °	'	Latitude °	'	Elevation Feet	Observed Gravity	Free Air	Bouguer
	Baie St Paul	70	30.5	47	26.5	45	980.8181	−.0273	−.0286
			31.7		27.0	68	.8210	−.0229	−.0252
			31.4		29.6	107	.8224	−.0217	−.0254
			30.9		31.6	134	.8137	−.0306	−.0352
			32.4		33.5	210	.8093	−.0310	−.0382
			34.8		37.8	1040	.7702	.0015	−.0339
			37.1		39.9	1109	.7659	.0005	−.0373
			38.1		40.8	1934	.7226	.0335	−.0324

PRINCIPAL FACTS FOR GRAVITY STATIONS

Road Traverse 1953 St. Urbain area — N. A. 85

Station No.	Station Name	Longitude °	Longitude ′	Latitude °	Latitude ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
		70	39.3	47	42.5	2472	980.7073	.0662	−.0180
			41.7		42.2	2592	.6977	.0684	−.0199
			43.3		43.6	2470	.7056	.0627	−.0214
			43.0		45.3	2456	.7080	.0612	−.0224
			44.3		46.8	2566	.7038	.0652	−.0222
			32.7		36.4	977	.7704	−.0021	−.0354
			32.7		34.7	288	.8069	−.0279	−.0377
			31.3		32.6	170	.8102	−.0325	−.0383
			31.8		28.9	175	.8188	−.0179	−.0239

Road Traverse 1954—Base stations Maniwaki to Senneterre and detail from Senneterre to Ottawa — N.A. 85

Station No.	Station Name	Longitude °	Longitude ′	Latitude °	Latitude ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	Dom. Obs. Front Steps	75	42.9	45	23.6	274.3	980.6220	−.0171	−.0265
	Maniwaki Stn.		58.6	46	22.4	569	.6907	−.0090	−.0285
	Maniwaki P.O.		58.6		22.6	561	.6907	−.0101	−.0292
	B.M. TS 49		43.0		33.6	850	.6859	−.0043	−.0333
	B.M. 717-G	76	04.3		43.8	754	.6969	−.0177	−.0434
	B.M. 727-G		24.9		53.6	1116	.6796	−.0156	−.0536
	B.M. 732-G		31.8	47	00.9	1244	.6812	−.0130	−.0554
	B.M. 753-G		37.7		08.9	1206	.6956	−.0142	−.0552
	O'Connell Lodge (1951)		32.2		02.3	1208	.6861	−.0136	−.0547
	B.M. 760-G		51.4		18.0	1174	.7166	−.0098	−.0498
	B.M. 771-G	77	08.9		34.2	1194	.7542	.0054	−.0353
	B.M. 781-G		20.8		48.7	1080	.7651	−.0162	−.0530
	B.M. 788-G		22.9	48	04.4	1045	.7999	−.0082	−.0438
	Senneterre CNR		14.7		23.5	1026	.8213	−.0172	−.0521
	Senneterre Air Base		13.6		23.4	1008	.8225	−.0175	−.0518
			15.3		22.8	1032	.8235	−.0133	−.0485
			18.5		18.5	1035	.8209	−.0092	−.0445
			20.2		13.7	1046	.8069	−.0150	−.0506
			22.0		08.8	1078	.8050	−.0076	−.0433
			22.3		02.4	1061	.7975	−.0061	−.0423
			21.4	47	56.5	1111	.7741	−.0160	−.0539
	Lowther		21.3		52.0	1107	.7662	−.0175	−.0552
			18.5		46.0	1152	.7554	−.0150	−.0543
			16.5		41.9	1168	.7572	−.0056	−.0454
			16.0		38.0	1141	.7604	.0009	−.0379
			13.1		37.2	1265	.7526	.0060	−.0371
			06.0		27.8	1187	.7419	.0020	−.0384
			01.9		26.0	1183	.7353	−.0022	−.0425
		76	57.9		21.3	1211	.7220	−.0059	−.0470
			46.0		14.0	1239	.7017	−.0126	−.0548
			41.1		12.3	1243	.6988	−.0126	−.0549
			27.3	46	57.6	1265	.6755	−.0117	−.0548
			51.2	47	20.5	1180	.7192	−.0104	−.0506
			48.8		27.1	1196	.7258	−.0122	−.0529
			43.8		29.9	1186	.7467	.0036	−.0368
			38.7		34.7	1171	.7585	.0067	−.0331

PRINCIPAL FACTS FOR GRAVITY STATIONS

Road Traverse 1952 Chicoutimi to Stoneham N.A. 85.

Station		Longitude		Latitude		Elevation Feet	Observed Gravity	Gravity Anomalies	
No.	Name	°	'	°	'			Free Air	Bouguer
		76	34.3	47	35.9	1180	980.7624	.0097	−.0305
			20.1	46	51.2	977	.6873	−.0174	−.0507
			16.7		49.3	864	.6915	−.0209	−.0504
			09.8		46.9	1019	.6825	−.0118	−.0347
			08.0		48.5	819	.6956	−.0199	−.0478
			08.5		51.6	779	.7001	−.0238	−.0504
			07.0		55.1	782	.7044	−.0245	−.0512
			01.1	47	01.8	855	.7044	−.0277	−.0568
		75	56.9		09.0	1062	.6996	−.0239	−.0600
			53.0		16.9	1023	.7062	−.0328	−.0676
		76	04.0		17.0	1222	.7161	−.0043	−.0459
			08.0		22.5	1188	.7208	−.0111	−.0515
			00.0		28.3	1218	.7174	−.0203	−.0618
		75	50.5		26.2	1229	.7176	−.0159	−.0578
		76	00.8	46	41.6	758	.6976	−.0133	−.0391
		75	56.4		38.2	680	.7027	−.0104	−.0336
			50.5		35.4	889	.6842	−.0051	−.0354
			30.0		33.2	755	.6705	−.0281	−.0538
			37.9		33.6	847	.6792	−.0113	−.0402
			33.2		33.7	768	.6757	−.0224	−.0485
			29.5		33.5	731	.6701	−.0311	−.0560
			30.2		28.4	921	.6597	−.0160	−.0473
	Lac des Iles		31.7		24.3	745	.6718	−.0143	−.0397
	Wabasee		32.2		20.1	668	.6722	−.0149	−.0376
			38.1		17.1	502	.6736	−.0245	−.0416
			40.3		13.2	695	.6731	.0010	−.0247
			39.5		09.3	665	.6716	.0005	−.0221
	N.D. de Laus		37.4		05.3	636	.6741	.0063	−.0153
			34.9		02.4	672	.6701	.0100	−.0129
			33.3	45	58.4	666	.6677	.0131	−.0095
			37.0		53.3	626	.6592	.0085	−.0129
			36.5		49.3	644	.6482	.0053	−.0167
			35.0		45.9	518	.6488	.0021	−.0155
			30.2		41.8	473	.6469	−.0009	−.0171
	Buckingham		25.1		35.3	429	.6482	.0061	−.0086
			26.5		38.7	581	.6463	.0133	−.0064
			25.6		33.0	163	.6597	−.0040	−.0095

Road Traverse Base Stations St. Siméon to Baie Comeau and local Observations N.A. 85.
Uffen 1954

No.	Name	Longitude °	'	Latitude °	'	Elevation Feet	Observed Gravity	Free Air	Bouguer
	Tadoussac (Dock)	69	42.7	48	08.3	25	980.8754	−.0343	−.0352
			42.1		10.6	49	.8583	−.0109	−.0277
	Grandes-Bergeronnes		32.1		14.7	103	.8834	−.0286	−.0321
			27.2		17.3	102	.8848	−.0312	−.0347
	St. Paul du Nord		13.8		34.9	37	.9180	−.0304	−.0317
			21.7		23.0	72	.8949	−.0325	−.0350
			18.8		26.1	122	.8977	−.0296	−.0338
			17.0		29.0	21	.9192	−.0220	−.0227
			05.1		41.3		.9088		

PRINCIPAL FACTS FOR GRAVITY STATIONS

Road Traverse Base Stations St. Siméon to Baie Comeau and local Observations N. A. 85 Uffen 1954

Station No.	Station Name	Longitude °	Longitude ′	Latitude °	Latitude ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	Forestville (Church)	69	03.6	48	44.8	286	980.9098	−.0300	−.0397
			08.5		34.1	13	.9266	−.0230	−.0234
			07.4		35.3	24	.9205	−.0297	−.0306
	Portneuf (Church)		05.9		37.1	38	.9182	−.0334	−.0347
			06.0		43.3	174	.9176	−.0305	−.0365
		68	41.8		55.3	226	.9486	−.0316	−.0323
		69	03.5		47.8	123	.9259	−.0337	−.0379
			00.0		49.0	163	.9274	−.0302	−.0357
		68	53.6		49.9	33	.9368	−.0355	−.0344
			47.1		53.7	170	.9364	−.0275	−.0333
			41.0		55.9		.9479		
	Chute aux Outardes		23.6	49	07.4	170	.9625	−.0219	−.0277
	(Church)		38.7		00.8	120	.9523	−.0270	−.0311
			36.5		03.0	16	.9644	−.0280	−.0285
			25.4		05.0	17	.9681	−.0272	−.0278
	Baie Comeau (Airport)		14.3		13.0	165	.9720	−.0213	−.0269
	Baie Comeau (DOCK)		09.0		13.2	13	.9820	−.0259	−.0263
			20.9		10.8	200	.9678	−.0189	−.0257
			16.5		11.8	65	.9791	−.0218	−.0240
			12.1		13.0	150	.9762	−.0185	−.0236

Looping to Rimouski and Observations in Gaspé Uffen 1954 N.A. 85

Station No.	Station Name	Longitude °	Longitude ′	Latitude °	Latitude ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	Rimouski (Church)	68	31.5	48	26.5	19	980.8955	−.0421	−.0428
	Mont Joli (Stn.)		11.3		35.3	261	.8899	−.0381	−.0469
	St. Angele de Merci		05.5		32.1	266	.8904	−.0384	−.0413
	St. Gabriel (Church)		09.2		26.0	1082	.8297	−.0072	−.0441
			13.9		22.8	674	.8500	−.0205	−.0435
			23.1		18.7	751	.8420	−.0151	−.0406
	St. Blandine (Church)		27.3		21.8	534	.8597	−.0225	−.0407

Road Traverse—1954 North Shore of Ottawa River West of Montreal and in Eastern Townships N.A. 85

Station No.	Station Name	Longitude °	Longitude ′	Latitude °	Latitude ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	Lachute	74	20.0	45	39.4	226	980.6470	−.0204	−.0281
	Brownsburg		24.3		40.5	362	.6357	−.0206	−.0329
			26.0		42.8	570	.6291	−.0111	−.0305
	Pine Hill		29.2		44.3	778	.6241	.0013	−.0252
			33.3		45.7	929*	.6240	.0133	−.0184
			34.4		46.8	935	.6281	.0162	−.0156
	Lost River		33.0		49.7	799	.6369	.0080	−.0193
	Lakeview		34.1		52.8	740	.6359	−.0033	−.0285
			34.2		55.8	624	.6385	−.0161	−.0374
	Arundel		36.9		57.9	625	.6333	−.0244	−.0457
			37.0	46	00.5	797	.6244	−.0210	−.0482
	St. Jovite Stn.		35.3		07.8	701	.6335	−.0320	−.0556
			36.4		05.4	674	.6321	−.0323	−.0553
	Brébeuf		40.0		04.3	649	.6404	−.0247	−.0468
			42.9		03.3	745	.6367	−.0178	−.0432

PRINCIPAL FACTS FOR GRAVITY STATIONS

Uffen 1954 *Altimeter

Station		Longitude		Latitude		Elevation Feet	Observed Gravity	Gravity Anomalies	
No.	Name	°	′	°	′			Free Air	Bouguer
	St. Rémi D'Amherst	74	45.7	46	00.5	686	980.6428	−.0131	−.0364
			47.2	45	59.3	721	.6434	−.0074	−.0319
			52.9		59.5	732	.6418	−.0082	−.0332
			54.7		56.2	739	.6395	−.0049	−.0301
	Namur		55.8		53.7	710	.6439	.0005	−.0237
			55.8		51.5	718	.6412	.0018	−.0226
	Notre Dame de la Paix		58.0		48.5	616	.6413	−.0031	−.0240
			58.4		44.5	526	.6428	−.0040	−.0219
			57.3		42.2	525	.6390	−.0045	−.0224
	Montebello		56.7		39.0	161	.6543	−.0187	−.0241
	St. Hubert	73	25.3		30.2	83	.6533	−.0137	−.0165
	St. Lambert		30.5		29.9	71	.6522	−.0155	−.0179
			29.7		28.2	56	.6511	−.0154	−.0173
	La Prairie		29.7		25.2	52	.6454	−.0170	−.0188
			32.2		24.1	58	.6426	−.0175	−.0195
			36.3		24.4	66	.6431	−.0168	−.0190
			40.7		24.9	87	.6437	−.0149	−.0179
			43.0		21.5	114	.6433	−.0077	−.0116
			47.1		21.3	102	.6452	−.0066	−.0101
	Maple Grove		50.3		19.2	91	.6488	−.0008	−.0039
	Beauharnois		52.8		18.9	81	.6491	−.0011	−.0038
			55.8		19.0	86	.6457	−.0041	−.0070
	St. Timothé	74	02.4		17.5	131	.6466	.0032	−.0012
	Valleyfield		07.9		15.4	145	.6473	.0082	.0035
			07.1		13.1	155	.6463	.0118	.0065
	Ste Barbe		11.9		09.8	167	.6468	.0184	.0127
	Port Lewis		16.9		10.2	164	.6436	.0143	.0087
	St. Amicet		21.8		08.5	166	.6384	.0119	.0063
			22.1		05.2	173	.6351	.0142	.0083
			27.3		02.1	173	.6314	.0152	.0093
	Dundee P.O.		30.6		00.0	155	.6284	.0136	.0083
	Dundee Centre		26.2		01.8	188	.6313	.0169	.0105
			24.1		00.5	195	.6335	.0217	.0151
			18.9		02.3	180	.6417	.0258	.0197
			14.3		03.8	185	.6455	.0278	.0214
	Huntingdon		10.9		05.2	165	.6482	.0265	.0209
			05.8		07.4	154	.6507	.0247	.0194
		73	59.9		07.9	144	.6518	.0241	.0192
		74	06.1		02.6	191	.6468	.0315	.0250
			00.3		02.3	311	.6349	.0314	.0208
		73	56.8		01.6	507	.6165	.0324	.0151
			50.3		02.4	484	.6115	.0240	.0075
			45.6		02.7	293	.6185	.0127	.0027
			41.2		02.8	240	.6161	.0051	−.0031
	Hemmingford		35.3		02.8	269	.6140	.0057	−.0035
			34.8		04.8	242	.6165	.0027	−.0056
			37.6		06.0	206	.6188	−.0002	−.0072
	Holton Stn.		39.6		08.2	195	.6227	−.0007	−.0073
			40.6		10.4	180	.6265	−.0016	−.0077
			35.3		12.3	205	.6236	−.0050	−.0120
			34.0		14.5	225	.6261	−.0039	−.0116
	St. Rémi		36.7		15.4	199	.6301	−.0029	−.0097

PRINCIPAL FACTS FOR GRAVITY STATIONS

Uffen 1954

Station		Longitude		Latitude		Elevation Feet	Observed Gravity	Gravity Anomalies	
No.	Name	°	′	°	′			Free Air	Bouguer
	St. Rémi	73	39.0	45	16.3	163	980.6363	–.0023	–.0078
			40.9		18.0	191	.6382	–.0002	–.0067
			42.7		14.2	142	.6400	.0027	–.0022
			48.1		14.5	130	.6484	.0094	.0050
			44.7		18.6	150	.6416	–.0016	–.0067
			48.2		17.2	127	.6505	.0072	.0029
	Vendome		53.7		15.7	130	.6497	.0089	.0045
			56.7		14.1	134	.6491	.0111	.0065
			59.9		12.9	138	.6460	.0102	.0005
		74	03.9		11.1	173	.6501	.0203	.0144
		73	55.8		09.0	133	.6519	.0215	.0170
	Howick CNR		51.2		11.5	132	.6512	.0169	.0124
	Aubrey		47.2		08.6	136	.6397	.0102	.0054
			45.0		06.0	166	.6303	.0066	.0010
			31.0		02.7	195	.6180	.0029	–.0037
	Portneuf	71	53.0	46	41.7	19	.7531	–.0274	–.0281
	Ste Anne de la Pérade	72	12.2		34.6	38	.7429	–.0222	–.0265
	St. Tite		33.9		43.4	457	.7316	–.0103	–.0259
	Grandmere		41.2		36.9	426	.7191	–.0159	–.0304
	Cap de la Madeleine		30.0		22.4	55	.7146	–.0335	–.0354
	Berthierville	73	10.7		05.0	29	.6881	–.0364	–.0374
	St. Sulpice		21.2	45	49.6	35	.6786	–.0221	–.0233
	Pointe aux Trembles		29.5		38.4	42	.6581	–.0250	–.0265
	Dorval		45.5		27.3	97	.6453	–.0160	–.0193
	Ste Anne de Bellevue		56.6		24.5	110	.6462	–.0092	–.0134
	St. Jérome		00.2		46.8	310	.6609	–.0097	–.0203
	St. Jacques		34.3		56.9	196	.6798	–.0168	–.0234
	Joliette		26.2		01.3	186	.6907	–.0134	–.0197
			26.0		04.1	193	.6112	–.0116	–.0127
	Lacolle		22.4		05.0	157	.6095	–.0126	–.0180
			19.3		05.9	130	.6088	–.0172	–.0116
			16.5		08.5	104	.6111	–.0212	–.0248
			16.1		11.7	107	.6155	–.0214	–.0251
			15.2		14.3	116	.6198	–.0202	–.0241
	St. Jean CPR		15.3		18.6	118	.6264	–.0198	–.0238
			34.0		30.0	151	.6499	–.0104	–.0155
			28.8		22.8	80	.6402	–.0160	–.0187
	St. Phillippe		28.6		21.2	116	.6366	–.0138	–.0177
			26.6		18.6	134	.6338	–.0109	–.0155
	St. Jacques le Mineur		25.0		16.8	180	.6283	–.0094	–.0155
			26.4		14.4	172	.6257	–.0091	–.0150
			27.9		11.2	191	.6165	–.0117	–.0182
			28.0		08.2	175	.6124	–.0128	–.0188
			21.8		08.9	183	.6112	–.0143	–.0205
			24.2		11.4	183	.6161	–.0132	–.0194
			22.6		14.8	156	.6221	–.0148	–.0201
			20.0		15.8	150	.6249	–.0142	–.0192
			19.6		18.2	159	.6275	–.0142	–.0197
	Cowansville	72	44.9		12.1	381	.6002	–.0116	–.0245
	Granby		43.8		24.0	387	.6244	.0053	–.0187
	Waterloo		31.0		20.5	701	.6350	.0407	.0169
	Magog		10.5		16.3	690	.5934	.0044	–.0191

PRINCIPAL FACTS FOR GRAVITY STATIONS

Uffen 1954

Station No.	Station Name	Longitude °	Longitude ′	Latitude °	Latitude ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	Sherbrooke	71	53.2	45	23.8	485	980.6131	−.0065	−.0230
	Richmond	72	08.6		39.5	393	.6908	.0394	.0260
	Marbleton	71	35.0		37.4	844	.6042	−.0020	−.0308
	Megantic	70	52.9		34.5	1310	.5535	−.0046	−.0492
	Disraeli	71	21.0		54.1	833	.6401	.0077	−.0207
	Black Lake		21.4	46	02.5	939	.6931	.0580	.0260
	Plessisville		46.2		13.0	504	.6813	−.0105	−.0277
	Thetford Mines		18.3		05.1	1029	.6599	.0294	−.0057
	Tring Junction	70	59.6		16.2	1068	.6443	.0008	−.0056
	Beauceville		45.7		12.3	633	.6488	−.0298	−.0513
	St. Georges		40.0		07.2	621	.6414	−.0307	−.0518
	Lac Etchemin		30.6		23.3	1260	.6366	.0004	−.0425
	St. Malachie		47.3		32.3	768	.6792	−.0171	−.0432
	St. Henri	71	04.0		41.5	290	.7104	−.0443	−.543

Uffen 1954 (Isle D'Orléans)

Station No.	Station Name	Longitude °	Longitude ′	Latitude °	Latitude ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	Quebec City	71	13.2	46	48.2	340	980.7289	−.0312	−.0428
	St. Pierre D'Orléans		04.4		53.4	293	.7440	−.0283	−.0383
			01.3		55.7	319	.7450	−.0284	−.0393
		70	57.8		58.4	212	.7530	−.0345	−.0417
			49.5	47	00.6	228	.7555	−.0338	−.0415
			52.4		56.1	192	.7489	−.0370	−.0436
			52.4		53.7	35	.7543	−.0428	−.0450
		71	02.1		51.8	342	.7385	−.0362	−.0445
			08.0		51.1	124	.7480	−.0368	−.0411

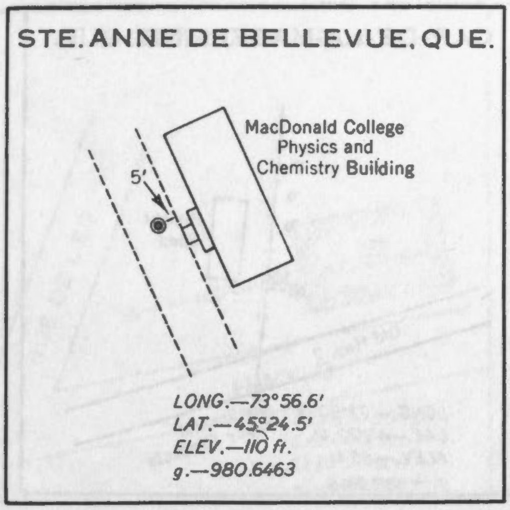
Uffen 1954

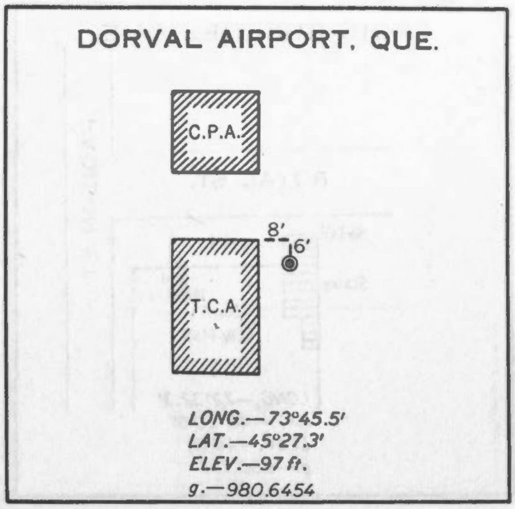
Station No.	Station Name	Longitude °	Longitude ′	Latitude °	Latitude ′	Elevation Feet	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
	Trois Rivières	72	32.3	46	20.6	49	980.7111	−.0349	−.0366
	St. Pierre les Bequets		12.5		30.3	100	.7228	−.0230	−.0364
	Manseau		00.3		22.2	309	.6909	−.0330	−.0436
	Victoriaville	71	57.5		03.5	435	.6898	.0058	−.0090
	Danville	72	01.0	45	47.5	450	.6920	.0339	.0187
	Drummondville		29.3		52.9	290	.6617	−.0200	−.0299
	Ste. Hélène de Bagot		43.9		43.8	241	.6650	−.0076	−.0158
	St. Hyacinthe		56.8		37.7	110	.6482	−.0276	−.0313
	St. Hilaire	73	11.9		33.4	85	.6554	−.0162	−.0191
	Beloeil		12.9		32.9	48	.6568	−.0176	−.0192

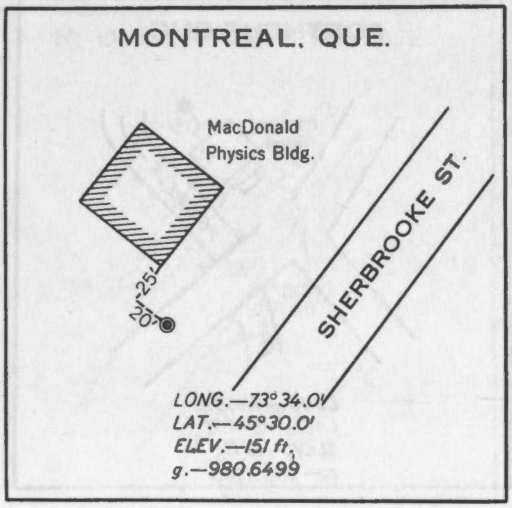
APPENDIX B

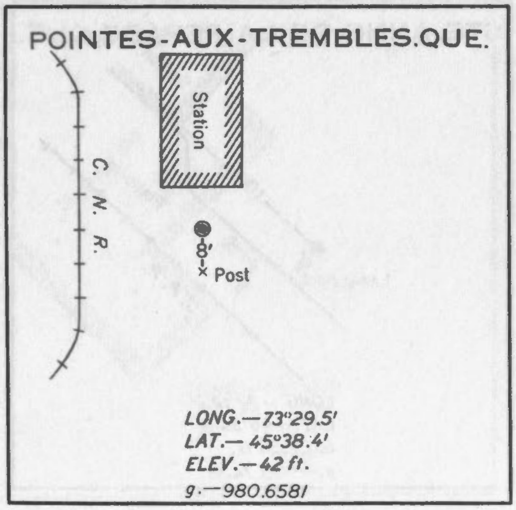
Descriptions of Sites of Gravimeter Bases

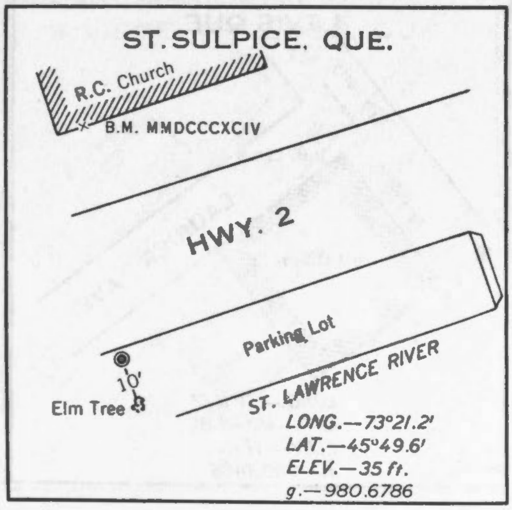
QUEBEC
HIGHWAY No. 2

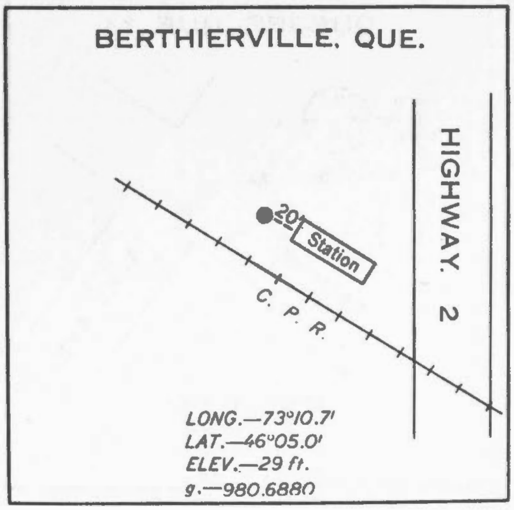












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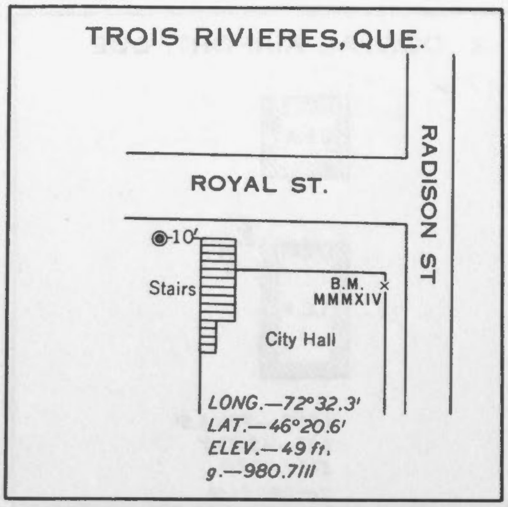

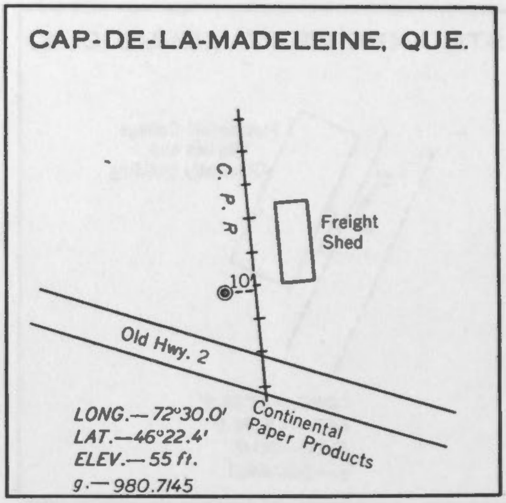

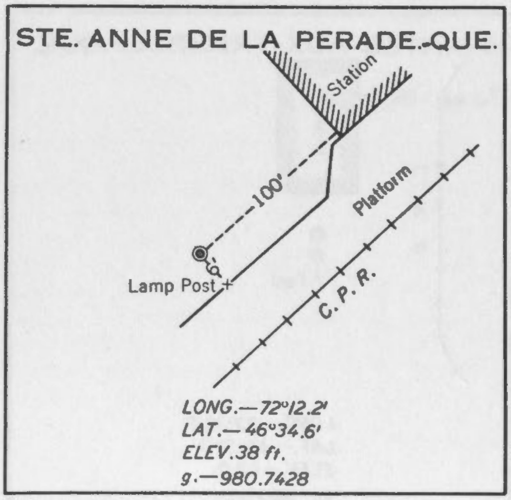

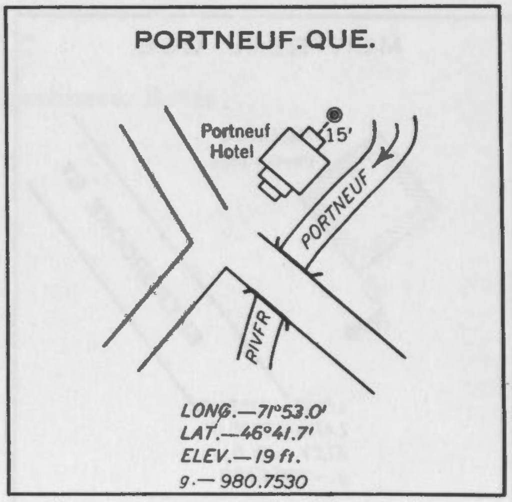

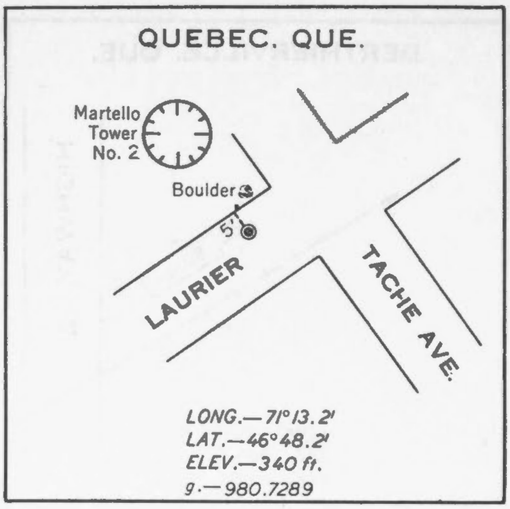

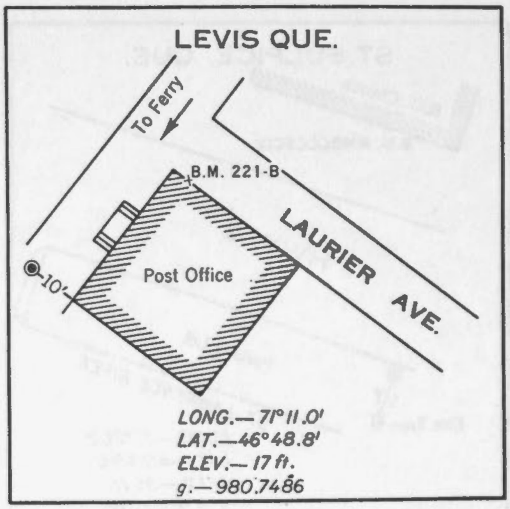

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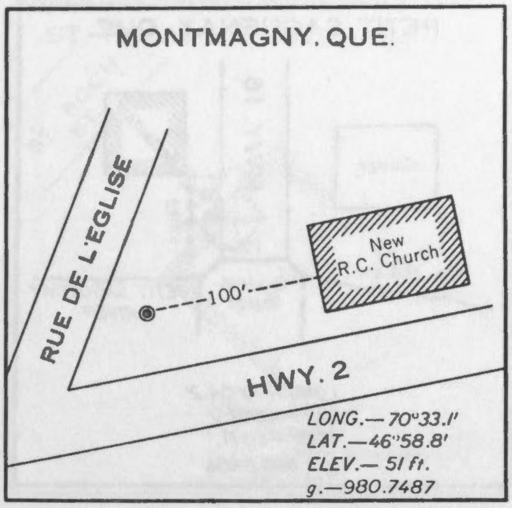

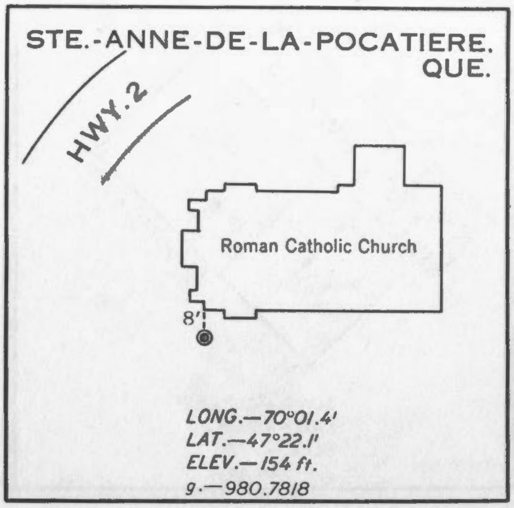

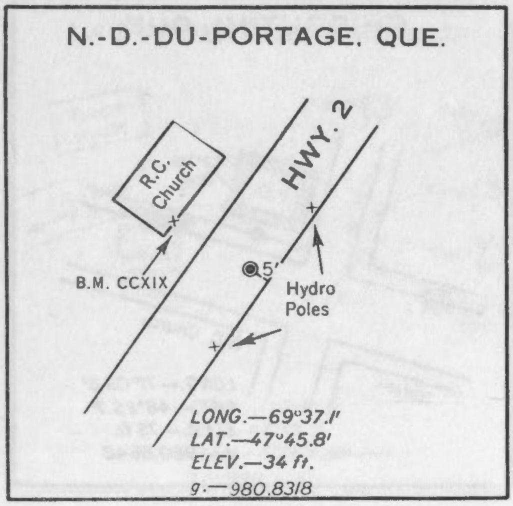

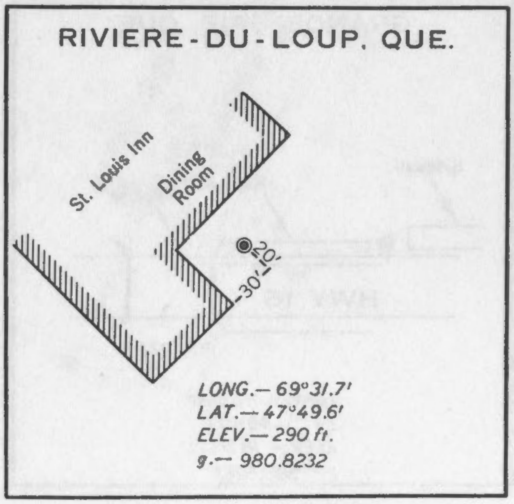

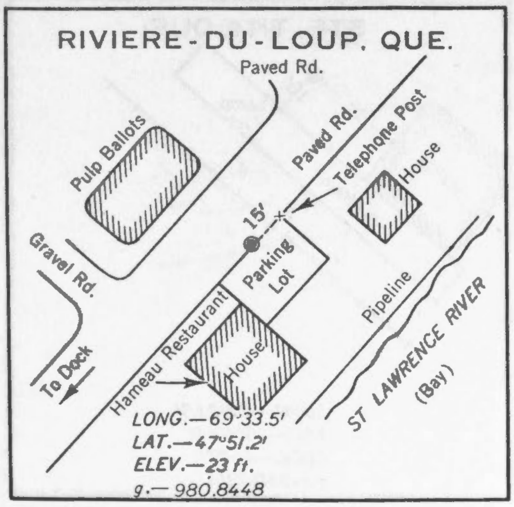

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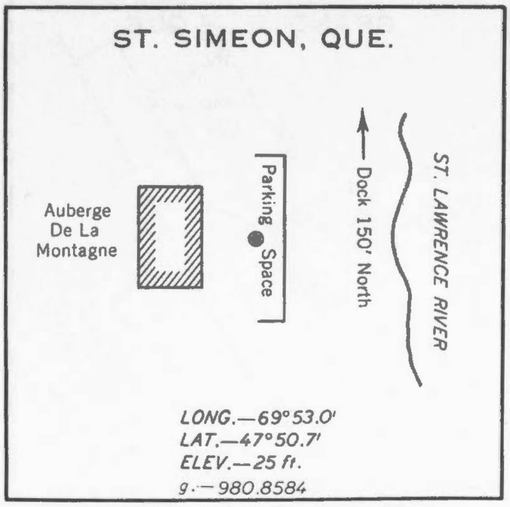
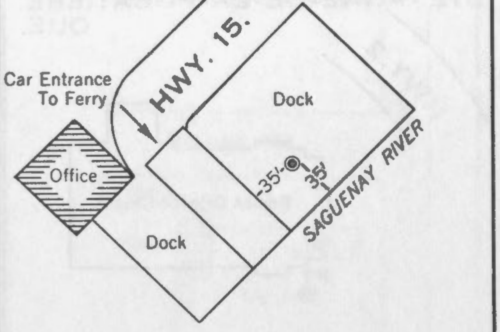


HIGHWAY No. 15 (CONT'D)

HIGHWAY No. 15

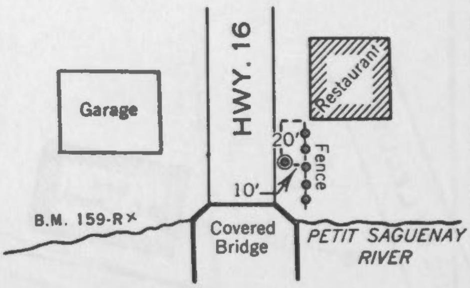
TADOUSSAC, QUE.



LONG.—69° 42.7'
LAT.—48° 08.2'
ELEV.—10 ft.
g.—980.8816

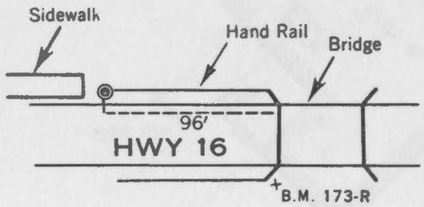
HIGHWAY No. 16

PETIT SAGUENAY, QUE.



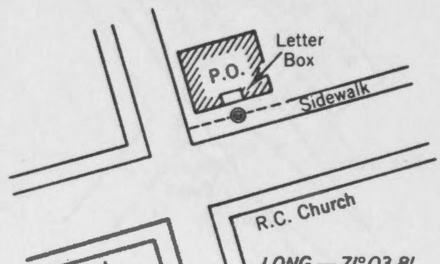
LONG.—70° 04.2'
LAT.—48° 12.9'
ELEV.—58 ft.
g.—980.8804

GRANDE BAIE, QUE.



LONG.—70° 51.0'
LAT.—48° 19.1'
ELEV.—18 ft.
g.—980.8713

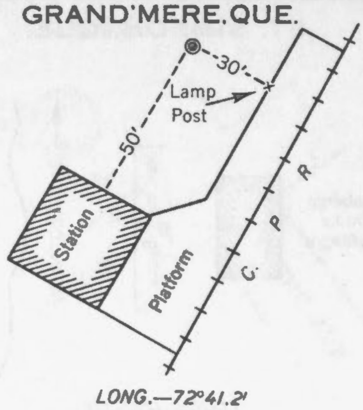
CHICOUTIMI, QUE.



LONG.—71° 03.8'
LAT.—48° 25.7'
ELEV.—75 ft.
g.—980.8648

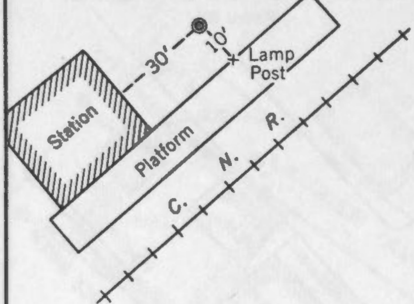
HIGHWAY No. 19

GRAND'MERE, QUE.



LONG.—72° 41.2'
LAT.—46° 36.9'
ELEV.—426 ft
g.—980.7191

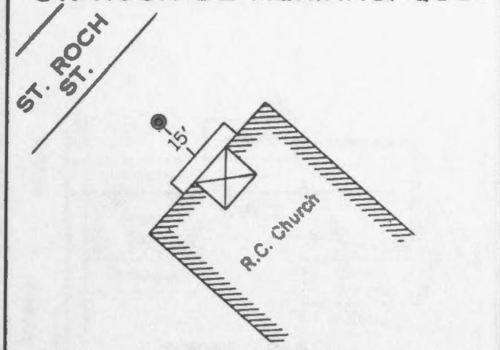
STE. TITE QUE.



LONG.—72° 33.9'
LAT.—46° 43.4'
ELEV.—457 ft.
g.—980.7316

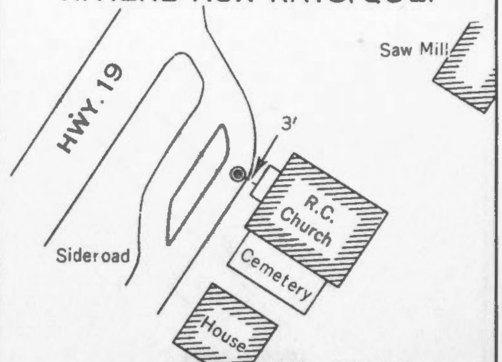
HIGHWAY No.19 (CONT'D)

ST.-ROCH-DE-MEKINAC, QUE.



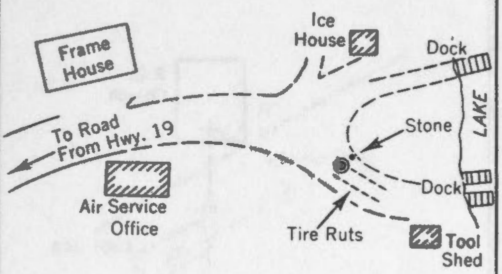
LONG.—72°46.3'
LAT.—46°48.9'
ELEV.—478 ft. (altimeter)
g.—980.7257

RIVIERE-AUX-RATS, QUE.



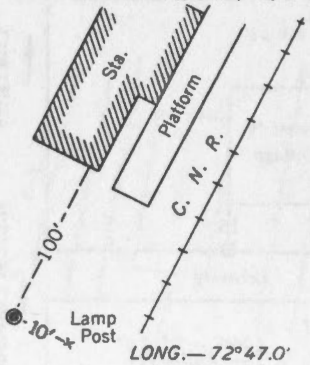
LONG.—72°53.6'
LAT.—47°12.6'
ELEV.—393 ft. (altimeter)
g.—980.7585

LAC A BEAUCE, (AIR) QUE.



LONG.—72°46.0'
LAT.—47°19.3'
ELEV.—689 ft. (altimeter)
g.—980.7650

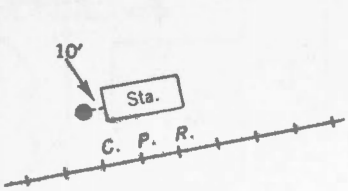
LA TUQUE, QUE.



LONG.— 72°47.0'
LAT.—47°26.3'
ELEV.— 545 ft.
g.— 980.7750

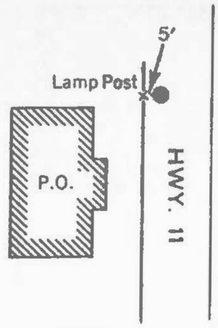
HIGHWAY 41

LACHUTE, QUE.



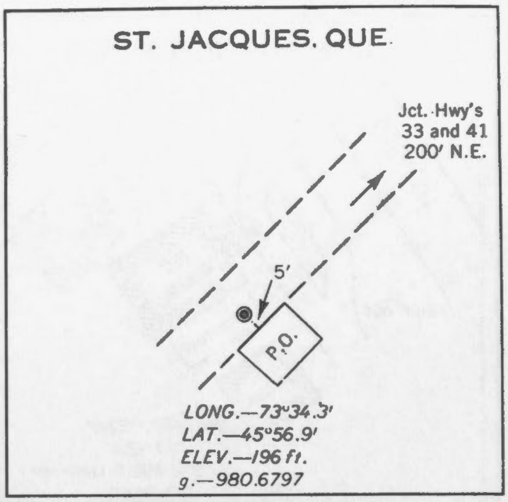
LONG.—74°20.0'
LAT.—45°39.4'
ELEV.—226 ft.
g.—980.6470

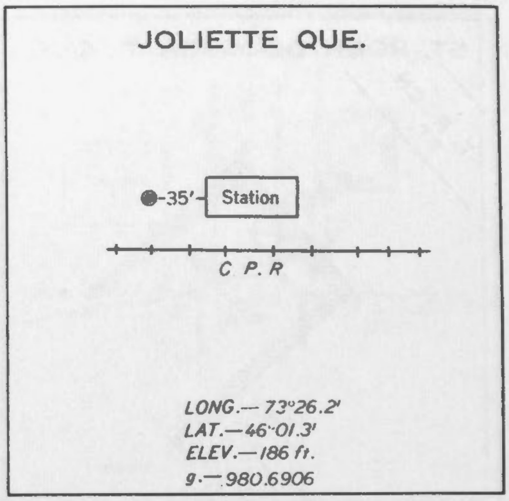
ST. JEROME, QUE.



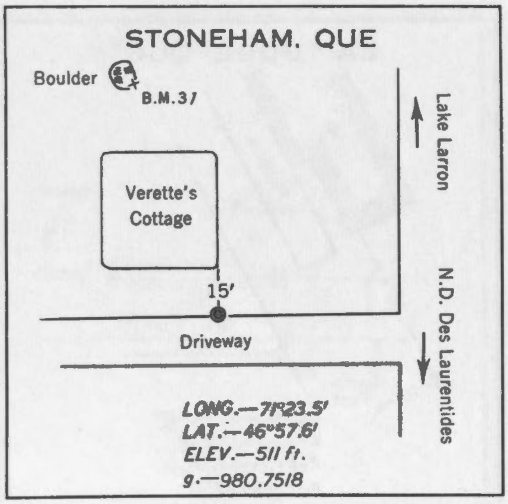
LONG.— 74°00.2'
LAT.—45°46.8'
ELEV.— 310 ft.
g.— 980.6609

HIGHWAY No. 41 (CONT'D)

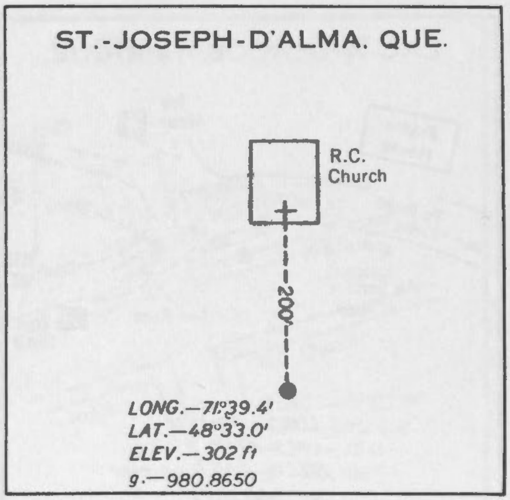


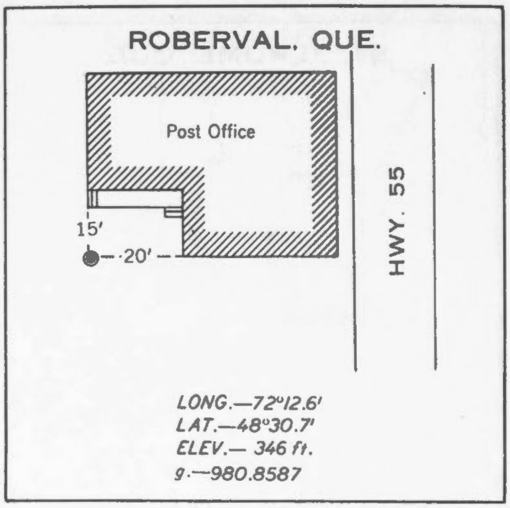


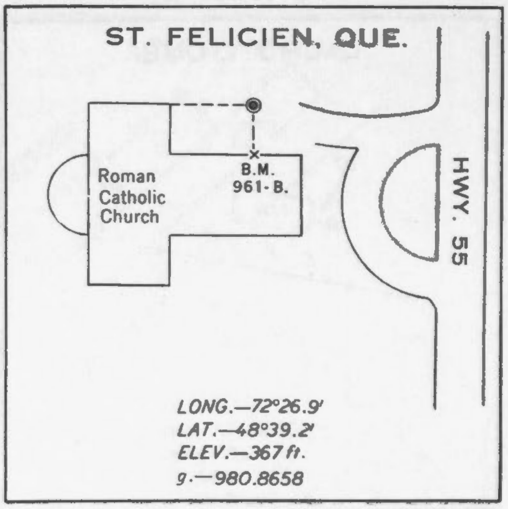
HIGHWAY No. 54



HIGHWAY No. 55

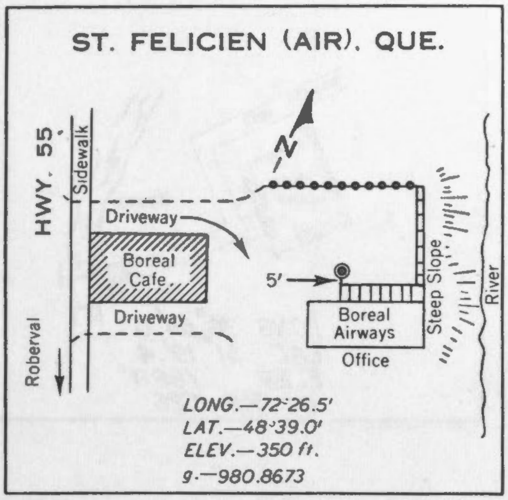


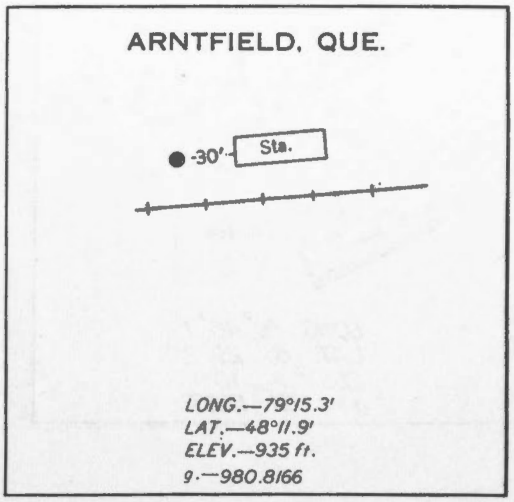


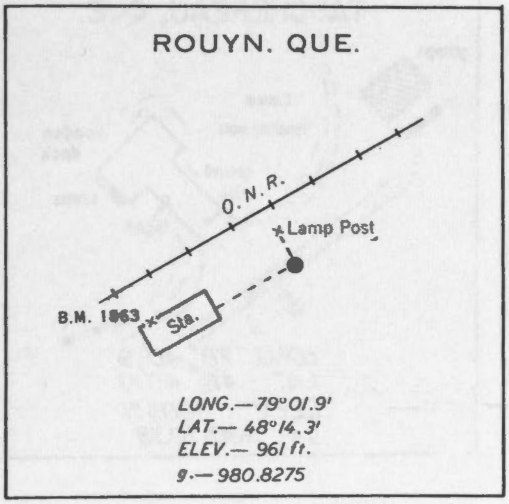


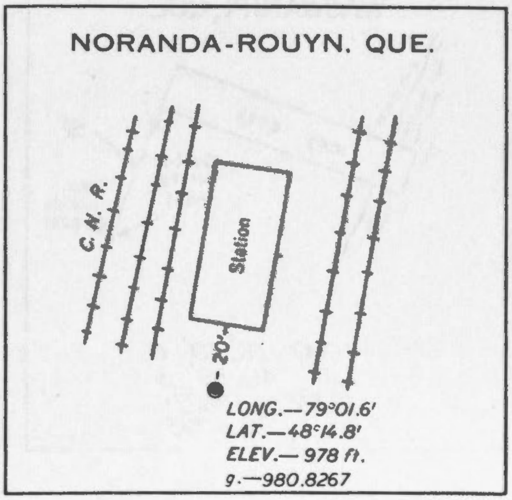
HIGHWAY No.55(CONT'D)

HIGHWAY No.59

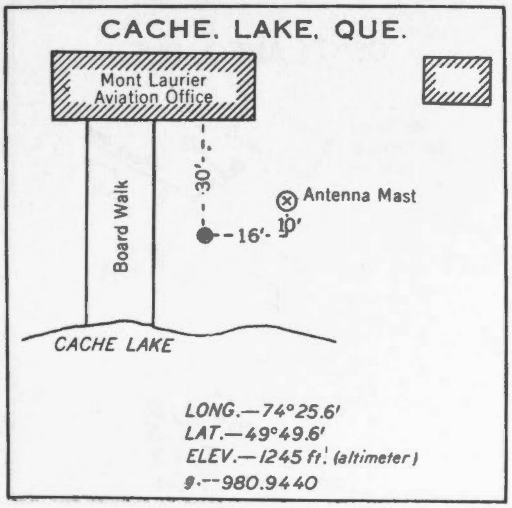


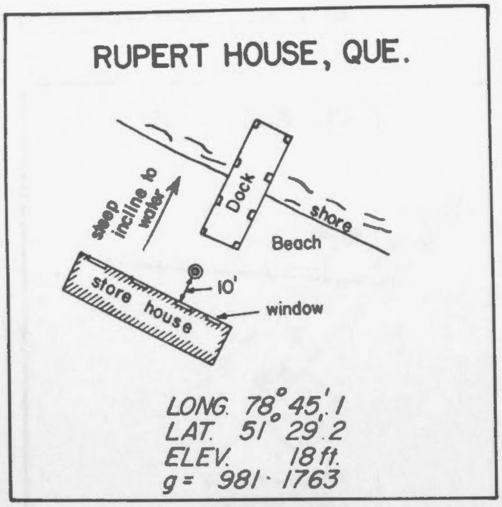


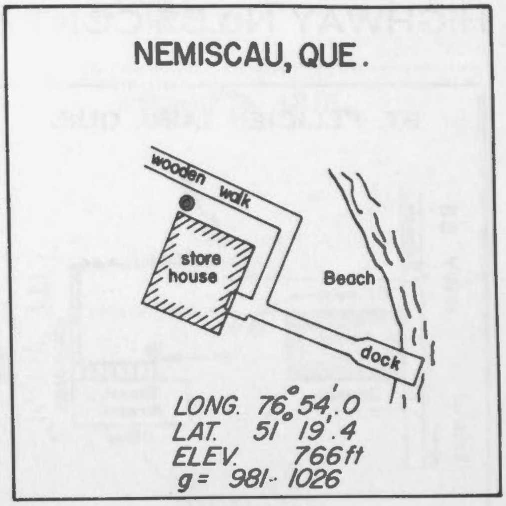


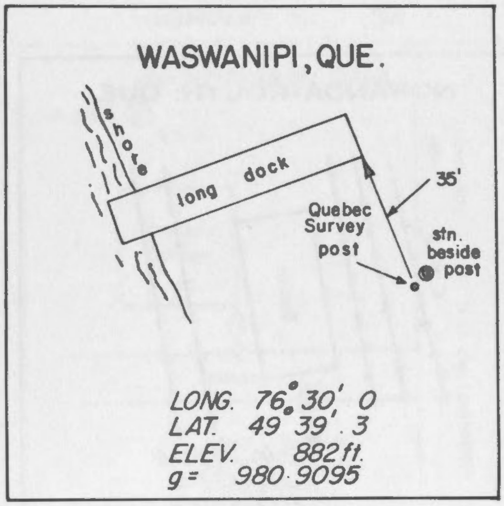


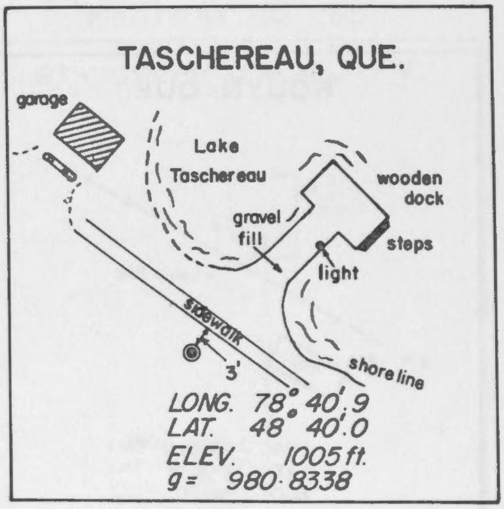
CHIBOUGAMAU ROAD

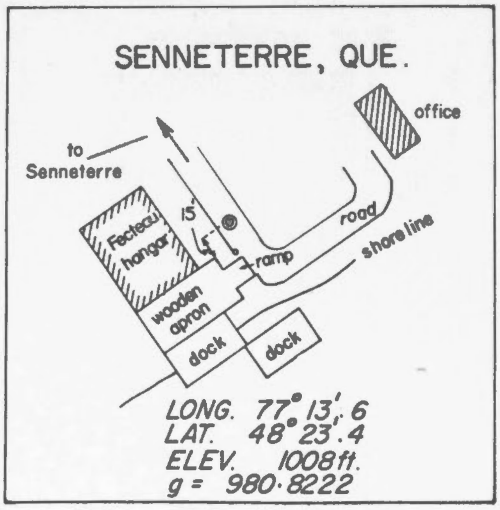



RUPERT HOUSE, QUE.
steep incline to water
Dock
shore
Beach
10'
store house
window
LONG. 78° 45'.1
LAT. 51° 29'.2
ELEV. 18 ft.
g = 981·1763

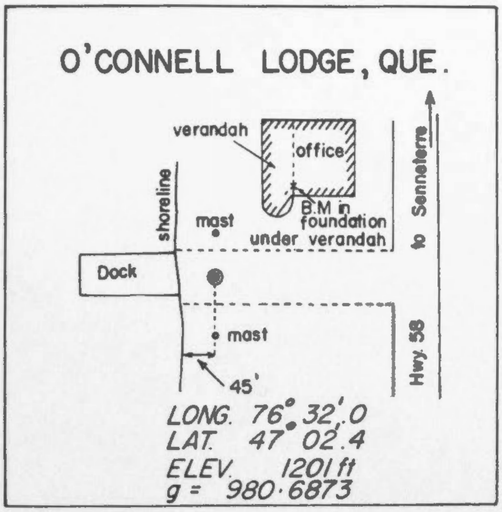

NEMISCAU, QUE.
wooden walk
store house
Beach
dock
LONG. 76° 54'.0
LAT. 51° 19'.4
ELEV. 766 ft
g = 981·1026


WASWANIPI, QUE.
shore
long dock
35'
Quebec Survey post
stn. beside post
LONG. 76° 30'.0
LAT. 49° 39'.3
ELEV. 882 ft.
g = 980·9095


TASCHEREAU, QUE.
garage
Lake Taschereau
wooden dock
gravel fill
steps
light
sidewalk
3'
shore line
LONG. 78° 40'.9
LAT. 48° 40'.0
ELEV. 1005 ft.
g = 980·8338


SENNETERRE, QUE.
office
to Senneterre
15'
Fecteau hangar
road
ramp
shore line
wooden apron
dock
dock
LONG. 77° 13'.6
LAT. 48° 23'.4
ELEV. 1008 ft.
g = 980·8222


OSKELANEO, QUE.
Northeast Air Express office
12'
shore line
small dock
LONG. 75° 12'.0
LAT. 48° 06'.5
ELEV. 1336 ft.
g = 980·7948


O'CONNELL LODGE, QUE.
verandah
office
shoreline
mast
B.M in foundation under verandah
to Senneterre
Dock
mast
45'
Hwy. 58
LONG. 76° 32'.0
LAT. 47° 02'.4
ELEV. 1201 ft
g = 980·6873

GRAVITY ANOMALY MAP OF QUEBEC (SOUTH OF 52°)

CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
DOMINION OBSERVATORIES

PUBLICATIONS

OF THE

Dominion Observatory

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VOLUME XIX No. 5

INVESTIGATIONS OF GRAVITY AND ISOSTASY IN THE SOUTHERN CANADIAN CORDILLERA

BY

G. D. GARLAND AND J. G. TANNER

EDMOND CLOUTIER, C.M.G., O.A., D.S.P.
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OTTAWA, 1957

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Investigations of Gravity and Isostasy in the Southern Canadian Cordillera

By G. D. Garland and J. G. Tanner

ABSTRACT: A regional gravity investigation of southern British Columbia and southwestern Alberta is described. The values of gravity are obtained from a network of closed circuits, subjected to a least squares solution, while the instrumental calibration is made with reference to stations established with the Cambridge pendulums. Maps of Bouguer and isostatic anomalies 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 do not strongly suggest a major crustal dislocation beneath it.

INTRODUCTION

This paper deals with gravity measurements made throughout the Canadian Cordilleran region in western Alberta and southern British Columbia in July and August 1954, with a North American gravimeter (*see* Figure 1). It includes also a description of the calibration of the instrument against pendulum stations between Lethbridge and Whitehorse. The gravity results are presented in the form of maps, showing Bouguer anomalies, and Airy isostatic anomalies for those stations for which full reductions were made. To assist in the interpretation, a selection of rock samples for density measurements was taken in the field, and vertical force magnetometer observations were taken along certain key traverses.

Previous to the work described here regional gravity measurements of the Dominion Observatory west from the Rocky Mountain foothills in Alberta, were limited to about 100 determinations.* Approximately 25 of these are pendulum stations, observed between 1915 and 1926 with the Mendenhall pendulum apparatus (Miller, 1929). The remainder are gravimeter stations observed in 1952, along the Trans-Canada Highway between Calgary and Vancouver by J. A. Robinson and M. M. Fitzpatrick of the Dominion Observatory, with an Atlas portable gravimeter. All of the 1952 sites were re-occupied during the course of the present observations.

THE GRAVITY OBSERVATIONS

Since the aim of the present work was not only to provide regional gravity coverage of southern British Columbia, but also to provide reliable values at base stations for future work, considerable care was given to the planning of closed circuits in which to make the observations. The outline of these circuits is shown in Figure 2, where it will be seen that the work was projected westerly from a line between Edmonton and Lethbridge in Alberta, to Hope and Vancouver. Four closed circuits are included between the line in Alberta and Hope, and a pair of independent connections link Hope to Vancouver. The line between Edmonton and Lethbridge was included in the observations since it includes three stations, Edmonton, Red Deer and Lethbridge, at which observations had been made with the Cambridge pendulums (Garland 1955).

*313 stations were observed throughout the northern Cordillera in 1953 when a survey was made along the Alaska Highway between Edmonton, Alberta, and Fairbanks, Alaska. (Oldham, 1957.)

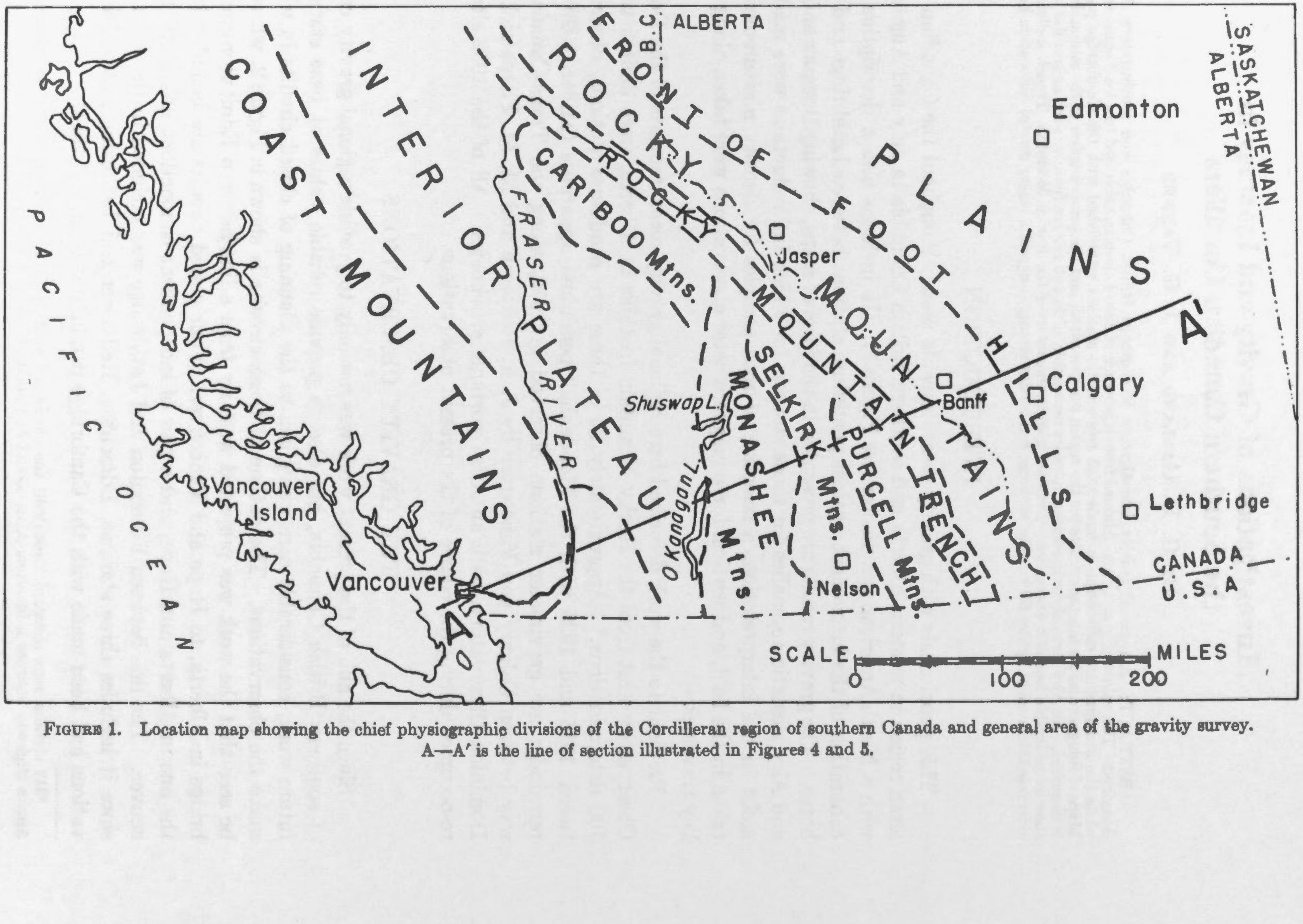


Figure 1. Location map showing the chief physiographic divisions of the Cordilleran region of southern Canada and general area of the gravity survey. A—A′ is the line of section illustrated in Figures 4 and 5.

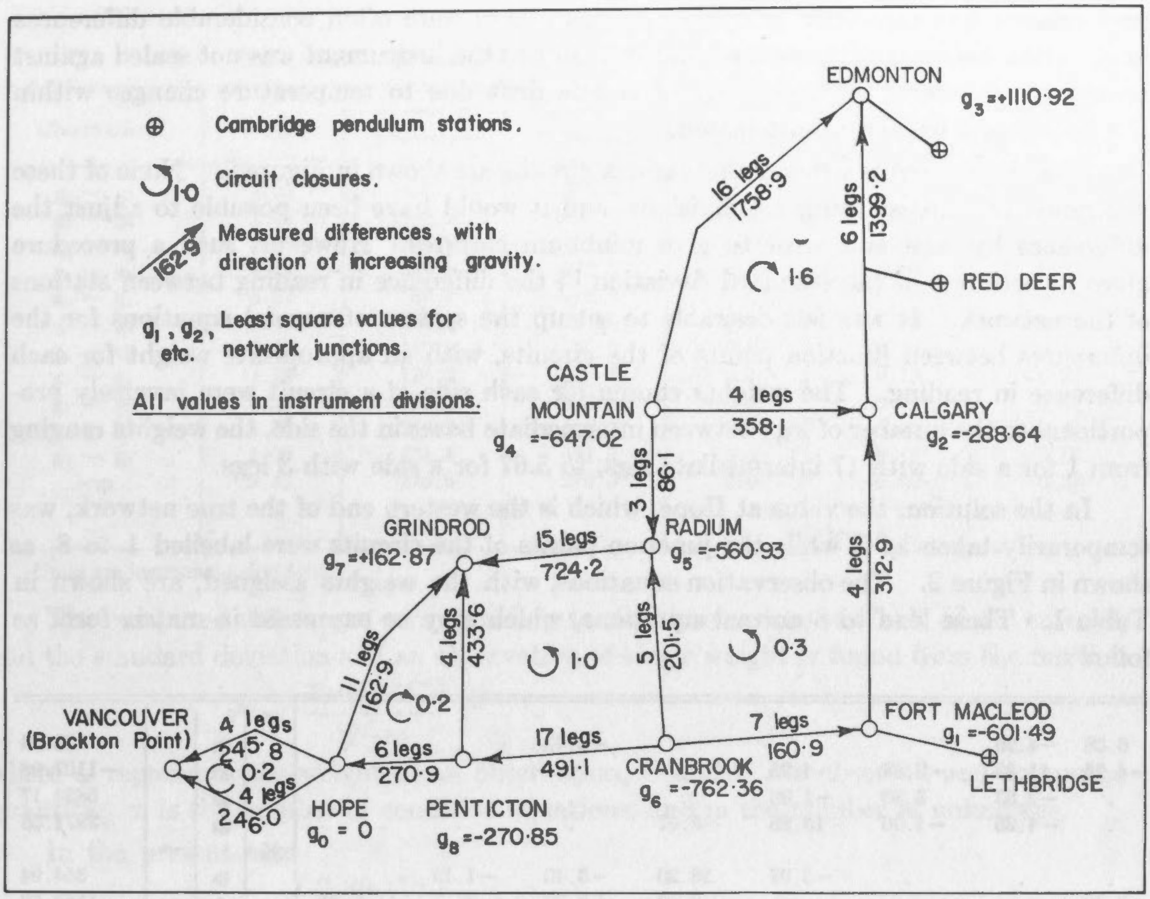


FIGURE 2. The primary gravity network, showing observed differences, closing errors and adjusted values.

All of the observations were made with a North American Gravimeter (No. 137), fitted with a long range geodetic dial. The scale constant of the instrument was known to be of the order of 0.242 milligal per division, but the final calibration was obtained from observations at pendulum stations, and are described below. The observations were carried forward around the circuits by the usual system of looping between intermediate bases, selected in such a way that repeat observations could by made within about one hour. In other words, if A and B are two such points, the measurements were made in the sequence A B A B, with the time between the two observations at either A or B being about one hour. Most of the intermediate bases were about 20 miles apart, and usually two or three stations could be observed on the final trip between them, without delaying the base readings. Differences in reading between bases were obtained by plotting the drift curve for each base, and measuring the distances between the curves corresponding to the times of the first reading at B and the second reading at A. In this method, the degree of parallelism between the drift lines at each base gives a measure of the behaviour of the instruments and of the reliability of the connection. For all of the present work the performance of the instrument was excellent. Out of 106 connections between base stations, 67 determinations had an uncertainty of less than 0.1 scale division, 38 had an uncertainty of 0.1 scale division, and one connection had an uncertainty of 0.2 scale division, all based on the parallelism, or lack of it, in the drift curves. This performance was especially gratifying because there were often considerable differences in elevation between adjacent base stations, and as the instrument was not sealed against changes in pressure, the possibility of erratic drift due to temperature changes within the instrument had been anticipated.

The closing errors around the various circuits are shown in Figure 2. None of these is serious, the largest being 1.6 divisions, and it would have been possible to adjust the differences by trial and error to give minimum closures. However, such a procedure gives no estimate of the standard deviation in the difference in reading between stations of the network. It was felt desirable to set up the system of normal equations for the differences between junction points of the circuits, with an appropriate weight for each difference in reading. The weights chosen for each side of a circuit were inversely proportional to the number of legs between intermediate bases in the side, the weights ranging from 1 for a side with 17 intermediate legs, to 5.67 for a side with 3 legs.

In the solution, the value at Hope, which is the western end of the true network, was temporarily taken as 0, while the junction points of the circuits were labelled 1 to 8, as shown in Figure 2. The observation equations, with the weights assigned, are shown in Table I. These lead to 8 normal equations, which may be expressed in matrix form as follows:

6.68	−4.25	.	.	.	−2.43	.	.		g_1		− 938.84
−4.25	11.33	−2.83	−4.25	.	.	.	.		g_2		−1107.98
.	−2.83	3.89	−1.06	.	.	.	.		g_3		5824.17
.	−4.25	−1.06	10.98	−5.67	.	.	.		g_4		−3874.55
								×		=	
.	.	.	−5.67	10.20	−3.40	−1.13	.		g_5		354.94
−2.43	.	.	.	−3.40	6.83	.	−1.00		g_6		−1565.58
						6.93	−4.25		g_7		2913.65
.	.	.	.	−1.13	.						
.	.	.	.	.	.	−4.25	8.08		g_8		−1567.25

The inverse of the matrix, obtained by the method of Fox (1950), is

.951602	.851595	.828534	.766948	.691991	.714991	.246674	.218238
.851595	.943627	.910589	.822368	.714990	.690634	.249481	.216701
.828534	.910589	1.147107	.835153	.720298	.685020	.250131	.216347
.766948	.822368	.835153	.869278	.734457	.670019	.251858	.215399
.691991	.714990	.720298	.734457	.751702	.651766	.253965	.214248
.714991	.690634	.685020	.670019	.651766	.757592	.241766	.220929
.246674	.249481	.250131	.251858	.253965	.241766	.301232	.188367
.218238	.216701	.216347	.215399	.214248	.220929	.188367	.250185

The solution follows directly:

$g_1 = -\ 601.49 \pm 0.74$ scale divisions
$g_2 = -\ 288.64 \pm 0.74$ scale divisions
$g_3 = 1110.92 \pm 0.81$ scale divisions
$g_4 = -\ 647.02 \pm 0.71$ scale divisions
$g_5 = -\ 560.93 \pm 0.66$ scale divisions
$g_6 = -\ 762.36 \pm 0.66$ scale divisions
$g_7 = 162.87 \pm 0.41$ scale divisions
$g_8 = -\ 270.85 \pm 0.37$ scale divisions

TABLE I

OBSERVED AND ADJUSTED NETWORK DIFFERENCES

Observation	Weight	Observed Difference	Calculated Difference	O—C	$w(O—C)^2$	Standard Deviation
$g_2 - g_4$	4.25	358.1	358.4	−0.3	0.38	0.31
$g_3 - g_2$	2.83	1399.2	1399.6	−0.4	0.45	0.39
$g_3 - g_4$	1.06	1758.9	1757.9	1.0	1.06	0.45
$g_2 - g_1$	4.25	312.9	312.9	0.0	0.00	0.41
$g_5 - g_4$	5.67	86.1	86.1	0.0	0.00	0.31
$g_5 - g_6$	3.40	201.5	201.4	0.1	0.03	0.35
$g_1 - g_6$	2.43	160.9	160.9	0.0	0.00	0.41
$g_7 - g_5$	1.13	724.2	723.8	0.4	0.18	0.57
$g_7 - g_8$	4.25	433.6	433.7	−0.1	0.04	0.31
g_7	1.55	162.9	162.9	0.0	0.00	0.41
$g_8 - g_6$	1.00	491.1	491.5	−0.4	0.16	0.57
$-g_8$	2.83	270.9	270.9	0.0	0.00	0.37
					Sum 2.30	

Units are instrument divisions.

The computed differences corresponding to the observations of Table II are entered, and the standard deviation s of an observation of single weight is found from the relation

$$s^2 = \frac{\Sigma\omega(O-C)^2}{n-m}$$

where ω represents the weight of an observation, O and C are observed and computed quantities, n is the number of condition equations, and m the number of unknowns.

In the present case

$$s = \left(\frac{2.30}{12-8}\right)^{\frac{1}{2}} = 0.76 \text{ division.}$$

The standard deviations of the various unknowns, shown above, were determined, in the usual way, by dividing the quantity 0.76 by the square root of the appropriate term in the principal diagonal of the inverse matrix. For example, the standard deviation of g_1 is

$$\frac{0.76}{(0.952)^{\frac{1}{2}}} = 0.74 \text{ division.}$$

Similarly, the variance and standard deviation of differences, such as $g_2 - g_4$, were found from the relation Var $(g_2 - g_4) = \text{Var}g_2 + \text{Var}g_4^{-2\,\text{cov}\,(g_2g_4)}$ with the covariance being given by the term of the inverse matrix in the (2,4) position.

Thus, $\text{Var}(g_2 - g_4) = (0.94 + 0.87 - 2 \times 0.82)\ 0.76^2$ and the standard deviation of $(g_2 - g_4)$ is 0.31 division. The standard deviations for the other differences are shown in Table I. It is this ease of estimating the reliability of the adjusted values that makes the formal solution, especially by the matrix methods, worth the additional computation.

The solution which has been outlined above has yielded relative values, in instrument divisions, for the key points of the network from a line in Alberta to Hope. It will be observed from Figure 2 that the connection from Hope to Vancouver consists of a single "circuit" of two sides, with small closure, and no further adjustment can be done here. The solution has indicated adjustments, usually less than one division, between the key points, as shown in the O—C column in Table I. The adjusted values for intermediate bases were obtained by simply apportioning these quantities between the component legs of each side of a circuit. Before actual values of gravity for the base stations can be obtained, it will be necessary to discuss the calibration of the instrument.

CALIBRATION OF THE GRAVIMETER

Previous to the present series of observations, no reliable calibration for the instrument was available for the range in gravity of interest. The key network included the Cambridge pendulum stations Lethbridge, Red Deer and Edmonton, covering a range of about 400 milligals. To provide a more reliable calibration, observations were made at the pendulum stations Grande Prairie, Fort St. John, Watson Lake and Whitehorse, so that the range was extended to almost 1000 milligals. These observations were made by flying from Edmonton to Whitehorse and returning the next day, the intermediate stations being observed on both days. Instrumental drift appeared to be small and uniform during the flights, and the simple means of the differences in reading from Edmonton were taken for use in calibration.

In adopting weights to use with the pendulum and gravimeter observations for the least squares solution, consideration has been given to the standard deviations in each case. The mean standard deviation of a determination with the Cambridge pendulums has been estimated as 0.30 milligal (Garland 1955). However, the pendulum connection from Edmonton to Lethbridge showed a somewhat larger scatter than is normal among the results with the individual pendulums, and the standard deviation for this determination has been taken as 0.60 milligal. The gravimeter connections from Edmonton to Red Deer and Lethbridge are largely within the network which has been described above, and the standard deviations have been taken as 0.10 and 0.12 milligal respectively. In the case of the special gravimeter observations at pendulum stations north of Edmonton, there was less rigorous control on the drift of the instrument, and the standard deviation in each case was estimated to be 1 scale division, or 0.24 milligal. The weights finally chosen are closely proportional to the inverse squares of these standard deviations.

In column 4, the Observed Values refer for the first 6 entries to the pendulum values, and for the final 6 to gravimeter observations with the above trial scale constant.

Quantities relevant to the solution are shown in Table II. The trial values for differences in gravity (shown in column 5) are pendulum values, while the trial values of the scale constant of the gravimeter is 0.24200 milligal per division. The quantity K is the correction to this trial scale constant, therefore the trial value of K is zero. If we let x_w, x_{wl}, be the corrections to the trial differences from Edmonton to Whitehorse, Watson Lake and so on, the following normal equations are obtained:

$$41\ x_{WH} - 14{,}528.75\ K = 1.25$$

$$41\ x_{WL} - 13{,}686.50\ K = 1.50$$

$$41\ x_{SJ} - 5{,}946.75\ K = -18.25$$

$$41\ x_{GP} - 3{,}750.00\ K = -10.00$$

$$160\ x_{RD}\ 24{,}570.72\ K = -47.52$$

$$104\ x_{L}\ 40{,}867.00\ K = -77.00$$

$$-14{,}528.75\ x_{WH} - 13{,}686.50\ x_{WL} - 5{,}946.75\ x_{SJ} - 3{,}750.00\ x_{GP} + 24{,}570.72\ x_{RD} + 40{,}867.00\ x_{L} + 38{,}806{,}866.61\ K = -35{,}282.43$$

TABLE II

CALIBRATION OF GRAVIMETER AGAINST PENDULUM STATIONS

Quantity	Standard Deviation	Weight	Observed Value	Trial Value	O—T	Calculated Value	O—C	w(O—C)²	X²
$g_{WH} - g_E$	0.30	16	581.10	581.10	0	581.11	−0.01	0.0016	0.001
$g_{WL} - g_E$	0.30	16	547.40	547.40	0	547.42	−0.02	0.0064	0.004
$g_{ST} - g_E$	0.30	16	238.60	238.60	0	238.15	0.45	3.2400	2.25
$g_{GP} - g_E$	0.30	16	150.40	150.40	0	150.15	0.25	1.0000	0.69
$g_{RD} - g_E$	0.30	16	−170.30	−170.30	0	−170.59	0.29	1.3456	0.93
$g_L - g_E$	0.60	4	−407.90	−407.90	0	−408.62	0.72	2.0736	1.44
$g_{WH} - g_E - 581.15K$	0.24	25	581.15	581.10	0.05	581.14	0.01	0.0025	0.002
$g_{WL} - g_E - 547.46K$	0.24	25	547.46	547.40	0.06	547.45	0.01	0.0025	0.002
$g_{ST} - g_E - 237.87K$	0.24	25	237.87	238.60	−0.73	238.16	−0.29	2.1025	1.46
$g_{GP} - g_E - 150.00K$	0.24	25	150.00	150.40	−0.40	150.16	−0.16	0.6400	0.45
$g_{RD} - g_E \quad 170.63K$	0.10	144	−170.63	−170.30	−0.33	−170.60	−0.03	0.1296	0.09
$g_L - g_E \quad 408.67K$	0.12	100	−408.67	−407.90	−0.77	−408.64	−0.03	0.0900	0.06
					Units are in milligals.			10.6343	7.38

The correction to the trial scale constant, with its standard deviation, is $K = -0.000046 \pm 0.00051$ and the final scale constant is $0.24200\ (1-0.000046) = 0.24199 \pm 0.00012$ milligal per scale division. The solution yields the following values for the corrections to the various differences from Edmonton, together with their standard deviations:

$$x_W = 0.01 \pm 0.29 \text{ mgal.}$$

$$x_{WL} = 0.02 \pm 0.29 \text{ mgal.}$$

$$x_{SJ} = -0.45 \pm 0.23 \text{ mgal.}$$

$$x_{GP} = -0.25 \pm 0.23 \text{ mgal.}$$

$$x_{RD} = -0.29 \pm 0.14 \text{ mgal.}$$

$$x_L = -0.72 \pm 0.25 \text{ mgal.}$$

These values represent the differences between the pendulum results and the adjusted values of gravity at the six stations, and they appear to be satisfactorily small. Indeed, it is only at Fort St. John, Red Deer and Lethbridge that the corrections to the pendulums are significantly greater than the standard error of the adjustment. The corrections to the pendulum determinations at Red Deer and Lethbridge are of the same sign, suggesting that errors in a series of observations made in one tour from base are related. Such a situation could have been predicted, since all pendulum observations north of Edmonton depend on one set of base measurements, while those south of Edmonton depend on another.

The final column of Table II gives the contributions to the value of X^2 for the solution. The sum of the column, X^2, is 7.38 on 5 degrees of freedom.

VALUES OF GRAVITY AT BASE STATIONS

With the scale constant determined in the previous section, and the adjusted differences between bases in scale divisions, values of gravity at all of the base points were obtained, relative to the Cambridge pendulum value at Edmonton, 981.1691 cm. per sec.^{2}. The reliability of this value relative to Ottawa has been discussed previously (Garland 1955).

To assist in the location of base stations, sketches have been prepared, Figure 3, showing their position relative to the surroundings. The key points of the network, that is the junctions between circuits, whose values were directly obtained in the adjustment, and one or two other stations which will probably form the starting points for future work, are described here in somewhat more detail. These points have either been marked with a Dominion Observatory tablet set in concrete, or referenced to an existing monument.

Cranbrook: The mark is a standard tablet, stamped "#6 — 1954", set in the pavement surface of the lane at the rear of Cranbrook post office, 8 inches from the building wall. The station is 8 feet south of the mark, at the same elevation.

Radium Junction: The location is at Radium Junction, in the gore of land between Highways 97, 1B, and old 97, south of a cut-off between the old and new highways. A standard tablet, stamped "#5 — 1954", is set in concrete flush with the ground, 4 feet southeast of a large double spruce. The station is 8 feet south of this tablet, at the same elevation. There is also a topographical survey monument, No. 82K21, about 100 feet northeast of the station.

Penticton: The location is on the waterfront, on the extension of Martin St., which leads to the wharf. A British Columbia legal surveys tablet, set in concrete flush with the ground, was used as the reference mark. The station is 10 feet west of the tablet, at the same elevation.

Grindrod: The station is at the northern edge of a grass-covered gore of land in the intersection of highway 97 and the road through Grindrod to Sicamous. A standard tablet, stamped "#3—1954", is set in concrete, 10 feet north of the only utility pole in the gore, and the station is 10 feet north of the tablet, at the same elevation.

Hope: The gravity base is in the grounds of the C.P.R. station, 65 feet east of the southeast corner of the station building. A standard tablet, stamped "#1—1954", is set in concrete flush with the ground, 10 feet north of a fir tree. The station is 15 feet north of the tablet, at the same elevation.

Cache Creek: This point was marked because it would be the logical starting point for work along the Cariboo highway to northern British Columbia. The location is in the vicinity of the junction of highways 1 and 2, at the north side of a road leading west from highway 2 to a bridge over Bonivar Creek. A standard tablet, stamped "#2—1954", is set in concrete flush with the ground 7 feet south of the north fence line of the road, directly opposite the door of the Cache Creek Hotel. The station is 10 feet south of this mark, at the same elevation.

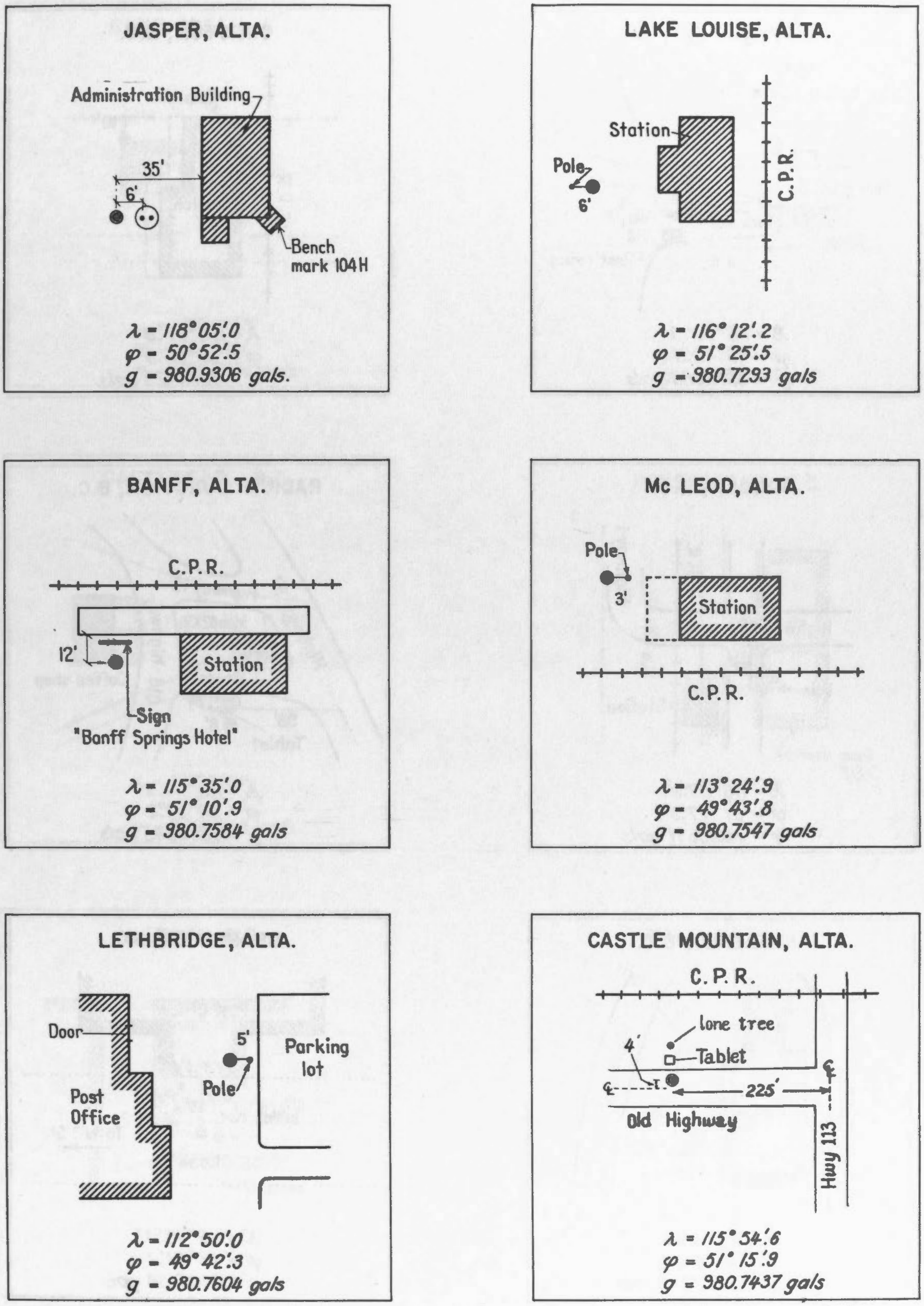


FIGURE 3a to g. Sketches showing locations of gravity bases. In each case, north is at the top. Scales are approximate, but are indicated by the distances given in each case.

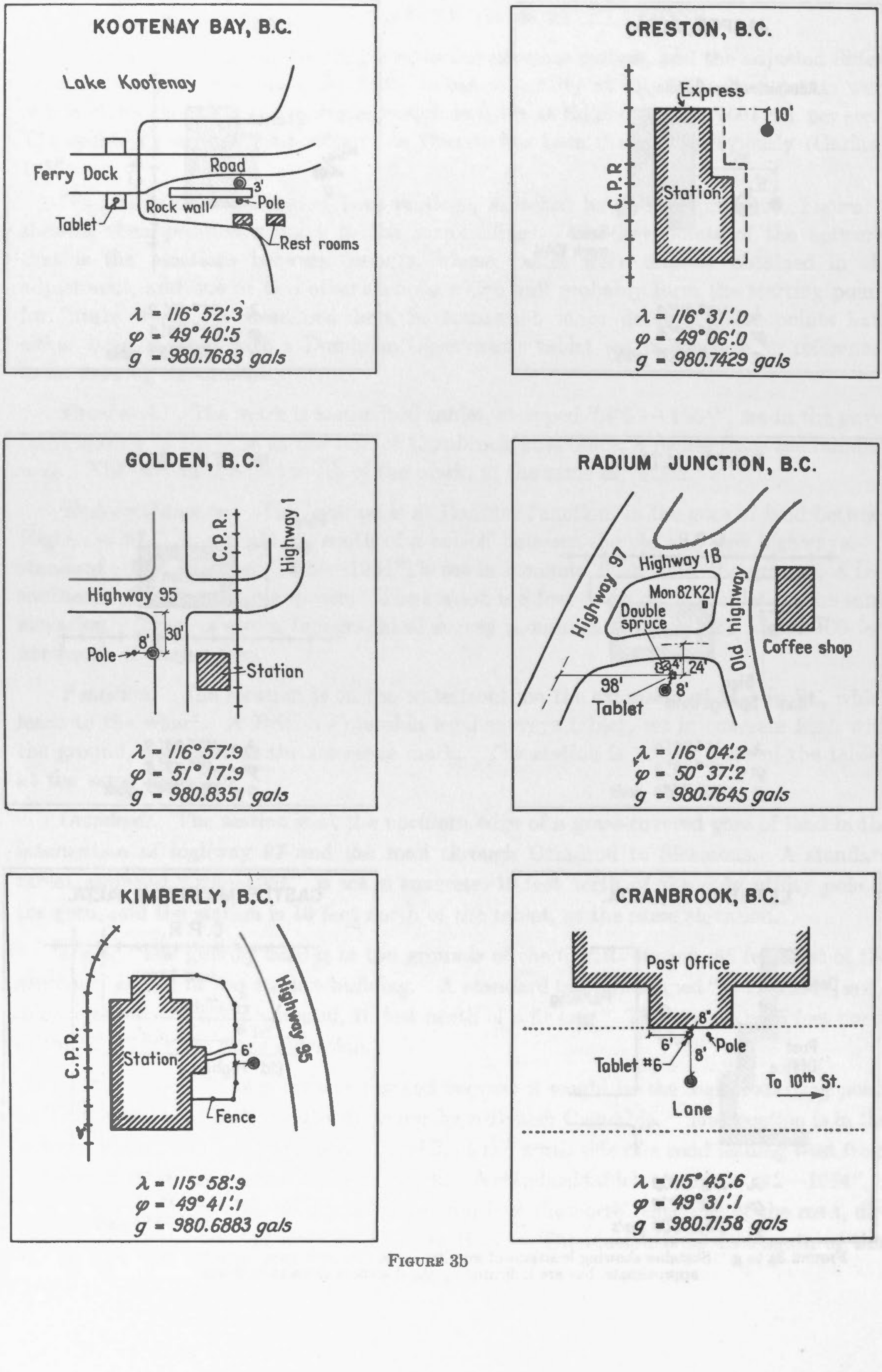

KOOTENAY BAY, B.C.
Lake Kootenay
Ferry Dock
Road
3'
Pole
Rock wall
Tablet
Rest rooms
λ = 116° 52'.3
φ = 49° 40'.5
g = 980.7683 gals
CRESTON, B.C.
Express
10'
C.P.R.
Station
λ = 116° 31'.0
φ = 49° 06'.0
g = 980.7429 gals
GOLDEN, B.C.
C.P.R.
Highway 1
Highway 95
30'
8'
Pole
Station
λ = 116° 57'.9
φ = 51° 17'.9
g = 980.8351 gals
RADIUM JUNCTION, B.C.
Highway 97
Highway 1B
Mon 82K21
Double spruce
Old highway
Coffee shop
98'
83.4'
24'
8'
Tablet
λ = 116° 04'.2
φ = 50° 37'.2
g = 980.7645 gals
KIMBERLY, B.C.
C.P.R.
Station
6'
Fence
Highway 95
λ = 115° 58'.9
φ = 49° 41'.1
g = 980.6883 gals
CRANBROOK, B.C.
Post Office
8'
6'
Pole
8'
Tablet #6
To 10th St.
Lane
λ = 115° 45'.6
φ = 49° 31'.1
g = 980.7158 gals

FIGURE 3b

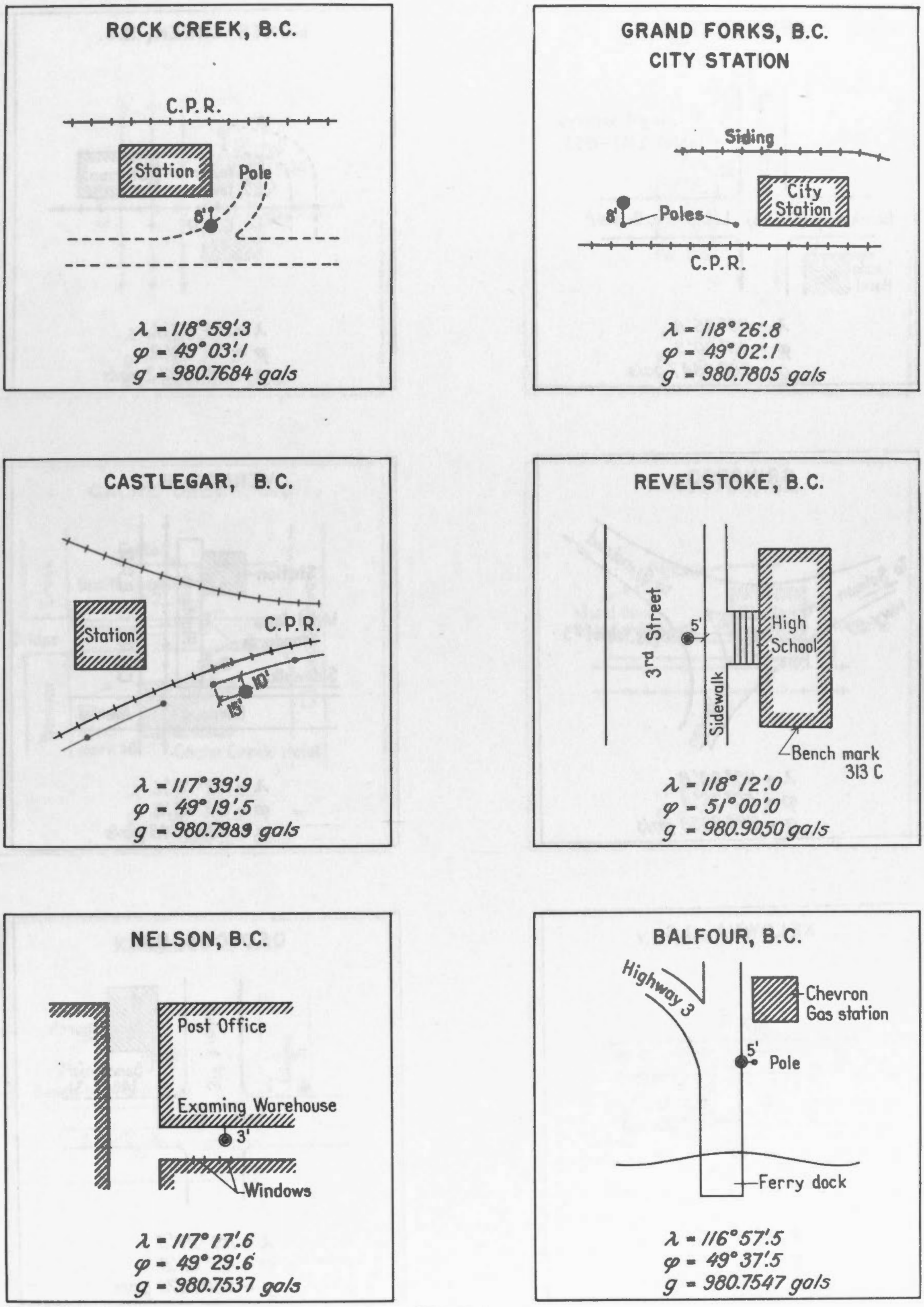

ROCK CREEK, B.C.
C.P.R.
Station
Pole
8'
λ = 118°59'.3
φ = 49°03'.1
g = 980.7684 gals
GRAND FORKS, B.C.
CITY STATION
Siding
City Station
8'
Poles
C.P.R.
λ = 118°26'.8
φ = 49°02'.1
g = 980.7805 gals
CASTLEGAR, B.C.
Station
C.P.R.
10'
15'
λ = 117°39'.9
φ = 49°19'.5
g = 980.7989 gals
REVELSTOKE, B.C.
3rd Street
5'
Sidewalk
High School
Bench mark 313 C
λ = 118°12'.0
φ = 51°00'.0
g = 980.9050 gals
NELSON, B.C.
Post Office
Examing Warehouse
3'
Windows
λ = 117°17'.6
φ = 49°29'.6
g = 980.7537 gals
BALFOUR, B.C.
Highway 3
Chevron Gas station
5'
Pole
Ferry dock
λ = 116°57'.5
φ = 49°37'.5
g = 980.7547 gals

FIGURE 3c

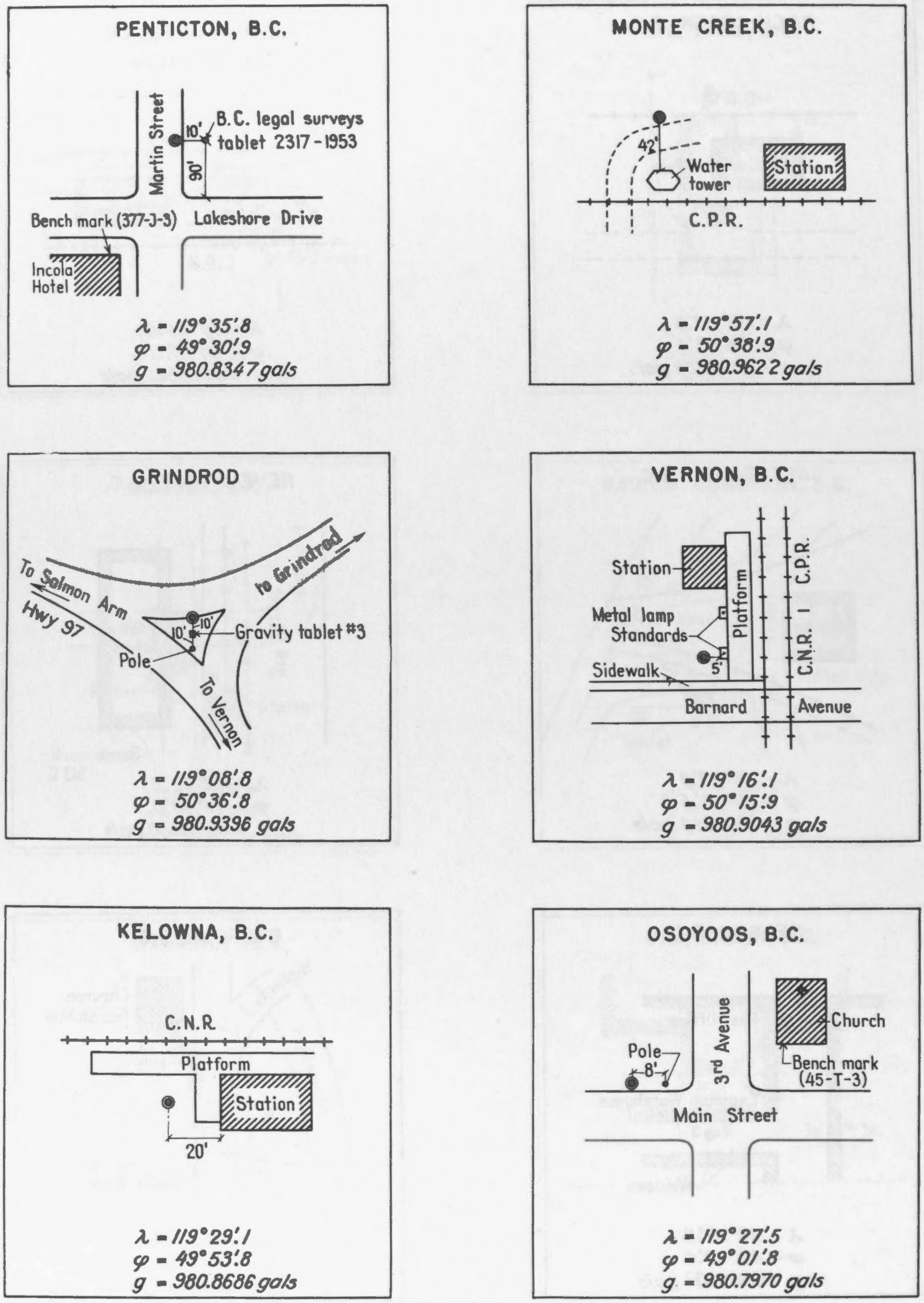

PENTICTON, B.C.
Martin Street
10'
B.C. legal surveys tablet 2317-1953
90'
Bench mark (377-J-3)
Lakeshore Drive
Incola Hotel
λ = 119° 35'.8
φ = 49° 30'.9
g = 980.8347 gals
MONTE CREEK, B.C.
42'
Water tower
Station
C.P.R.
λ = 119° 57'.1
φ = 50° 38'.9
g = 980.9622 gals
GRINDROD
To Salmon Arm
Hwy 97
to Grindrod
10'
10'
Gravity tablet #3
Pole
To Vernon
λ = 119° 08'.8
φ = 50° 36'.8
g = 980.9396 gals
VERNON, B.C.
Station
Platform
C.P.R.
Metal lamp Standards
C.N.R. I
5'
Sidewalk
Barnard
Avenue
λ = 119° 16'.1
φ = 50° 15'.9
g = 980.9043 gals
KELOWNA, B.C.
C.N.R.
Platform
Station
20'
λ = 119° 29'.1
φ = 49° 53'.8
g = 980.8686 gals
OSOYOOS, B.C.
3rd Avenue
Church
Pole
8'
Bench mark (45-T-3)
Main Street
λ = 119° 27'.5
φ = 49° 01'.8
g = 980.7970 gals

FIGURE 3d

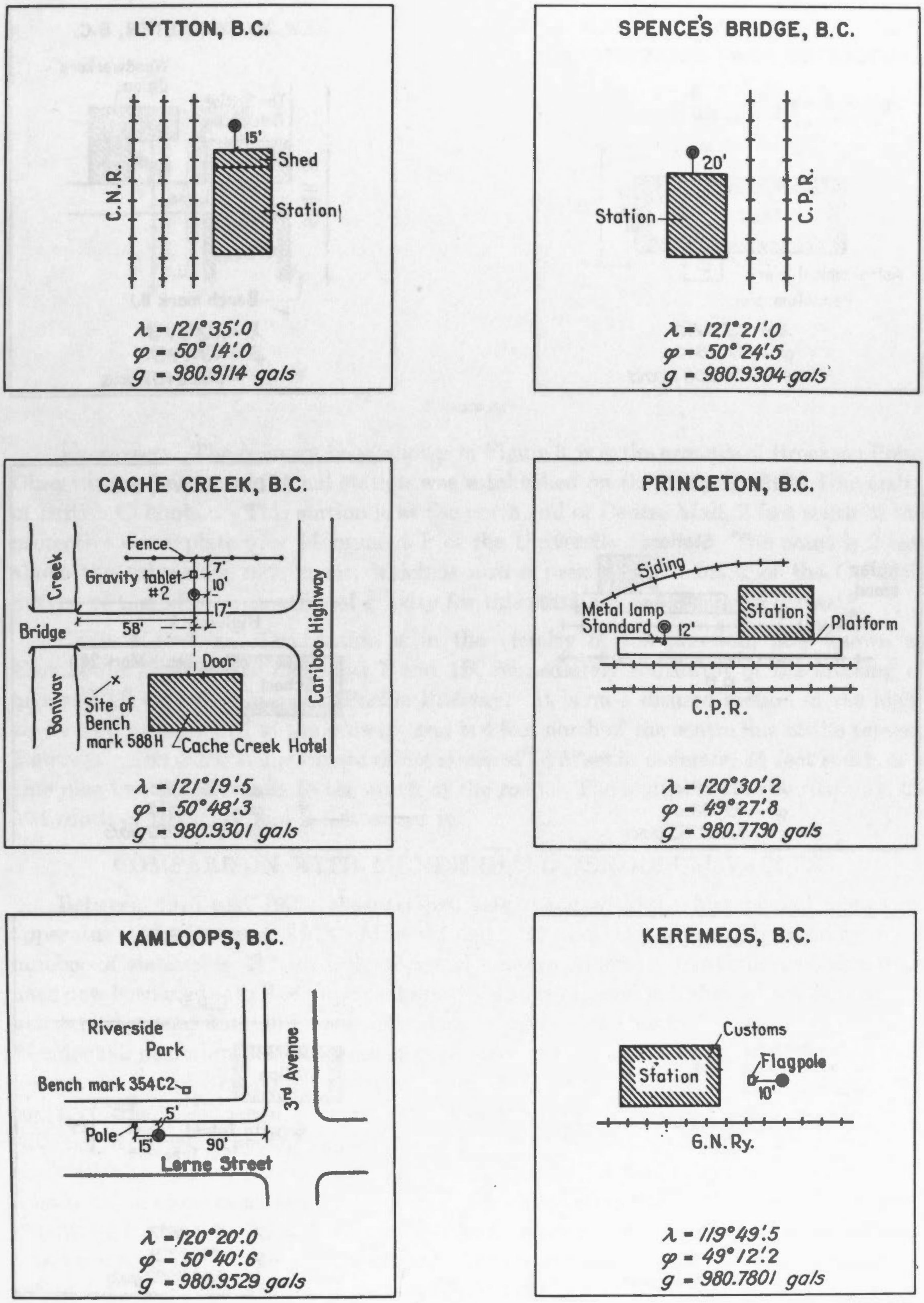
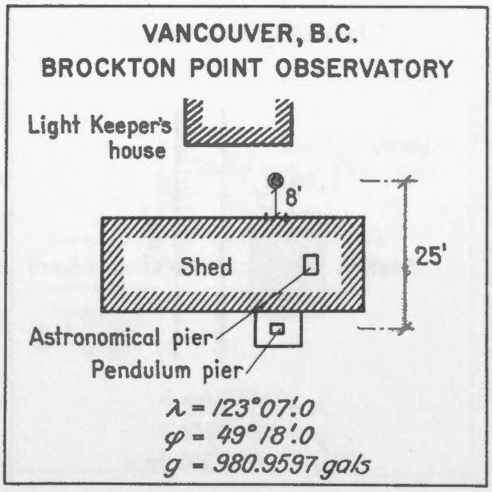
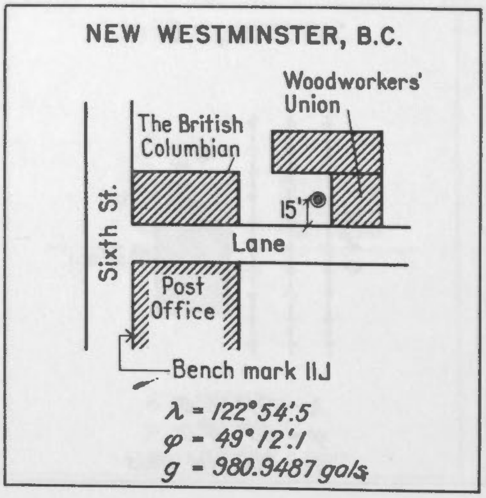
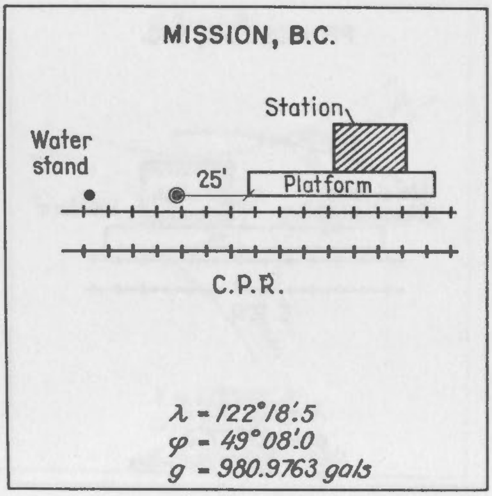
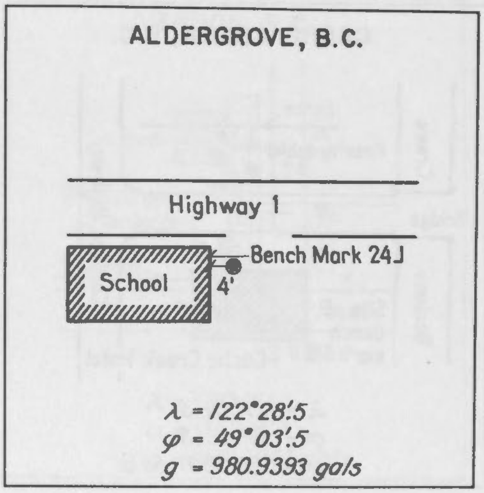

LYTTON, B.C.
C.N.R.
15'
Shed
Station
λ = 121° 35'.0
φ = 50° 14'.0
g = 980.9114 gals
SPENCE'S BRIDGE, B.C.
20'
Station
C.P.R.
λ = 121° 21'.0
φ = 50° 24'.5
g = 980.9304 gals
CACHE CREEK, B.C.
Fence
Creek
Gravity tablet #2
7'
10'
17'
58'
Bridge
Door
Bonivar
Site of Bench mark 588H
Cache Creek Hotel
Cariboo Highway
λ = 121° 19'.5
φ = 50° 48'.3
g = 980.9301 gals
PRINCETON, B.C.
Siding
Metal lamp Standard
12'
Station
Platform
C.P.R.
λ = 120° 30'.2
φ = 49° 27'.8
g = 980.7790 gals
KAMLOOPS, B.C.
Riverside Park
Bench mark 354C2
5'
Pole
15'
90'
3rd Avenue
Lorne Street
λ = 120° 20'.0
φ = 50° 40'.6
g = 980.9529 gals
KEREMEOS, B.C.
Customs
Station
Flagpole
10'
G.N.Ry.
λ = 119° 49'.5
φ = 49° 12'.2
g = 980.7801 gals

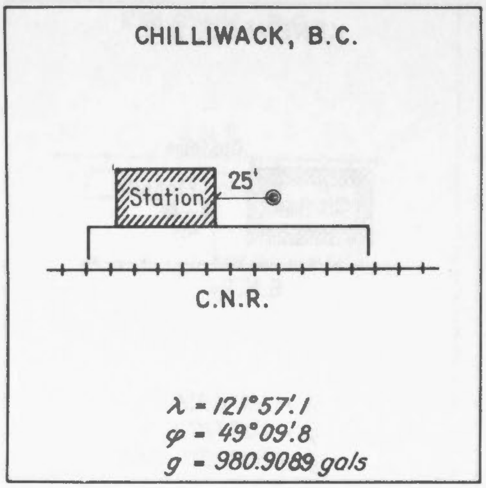
FIGURE 3e


VANCOUVER, B.C.
BROCKTON POINT OBSERVATORY
Light Keeper's house
8'
25'
Shed
Astronomical pier
Pendulum pier
λ = 123°07'.0
φ = 49°18'.0
g = 980.9597 gals


NEW WESTMINSTER, B.C.
Woodworkers' Union
The British Columbian
Sixth St.
15'
Lane
Post Office
Bench mark 11J
λ = 122°54'.5
φ = 49°12'.1
g = 980.9487 gals


MISSION, B.C.
Station
Water stand
25'
Platform
C.P.R.
λ = 122°18'.5
φ = 49°08'.0
g = 980.9763 gals


ALDERGROVE, B.C.
Highway 1
Bench Mark 24J
School
4'
λ = 122°28'.5
φ = 49°03'.5
g = 980.9393 gals


CHILLIWACK, B.C.
Station
25'
C.N.R.
λ = 121°57'.1
φ = 49°09'.8
g = 980.9089 gals

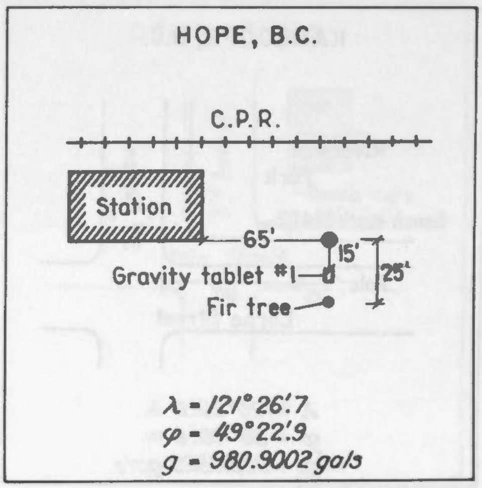
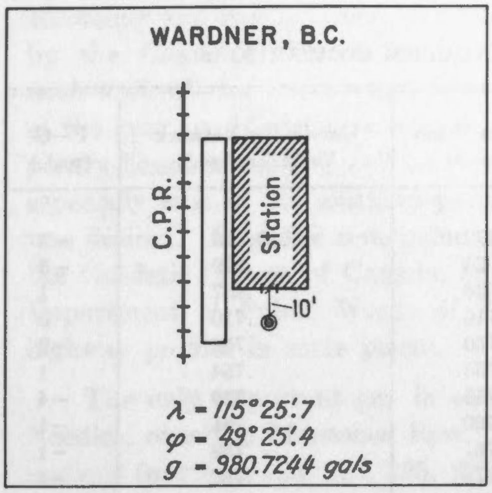

HOPE, B.C.
C.P.R.
Station
65'
15'
25'
Gravity tablet #1
Fir tree
λ = 121°26'.7
φ = 49°22'.9
g = 980.9002 gals

FIGURE 3f



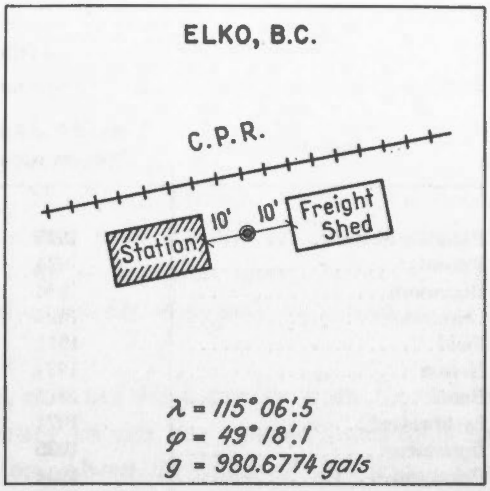


FIGURE 3g

Vancouver: The primary base, shown in Figure 3, is in the grounds of Brockton Point Observatory, but an additional station was established on the campus of the University of British Columbia. This station is at the north end of Centre Mall, 2 feet south of the protective cover plate over Monument P of the University Survey. The point is 2 feet above the subsurface monument, which is also a precise bench mark of the Geodetic Survey of Canada. The value of gravity for this station is 980.9366 cm. per sec.^{2}.

Castle Mountain: The station is in the vicinity of the junction, now known as Eisenhower Junction, of highways 1 and 1B, immediately southwest of the crossing of highway 1B over the Canadian Pacific Railway. It is on a disused section of the highway which runs parallel to the railway, and is 4 feet north of the centre line of the present highway. The mark is a standard tablet stamped "#6" set in concrete, 3¼ feet south of a lone pine tree which stands to the north of the road. The station is on the roadway, 25 feet south of the mark and 2 feet above it.

COMPARISON WITH MENDENHALL PENDULUM VALUES

Between 1915 and 1925, observations were made with the Mendenhall pendulum apparatus (MacDiarmid 1918, Miller 1929), of the Dominion Observatory at a number of stations in British Columbia and western Alberta. Gravimeter observations have now been made at all of these that are still accessible, and in Table III the comparison between the pendulum and network values is made. It should be explained that the Mendenhall pendulum stations were in most cases in the basements of buildings, and that the gravimeter observations were usually made just outside these buildings, when they could be identified, some 5 or 6 feet above the pendulum sites. Previous experience with the Mendenhall pendulum values had shown that errors of several milligals could be expected, and since these stations were not being used for calibration, the time was not usually taken to make an exact relocation of the observation site. The summary of mean differences by years in Table III confirms that an error of between two and three milligals is to be expected in the pendulum values. The errors appear to be consistently negative, except for the pendulum observations made in 1924, which are quite well centred about the network values.

TABLE III

GRAVIMETER AND MENDENHALL PENDULUM COMPARISONS

Station	Date of Pendulum Observation	Pendulum Value (cm/sec.²)	Gravimeter Network Value (cm/sec.²)	P—G (mgl.)
Paradise Mine*..................	1925	980.472	980.475	−3
Phoenix*..................	1924	.624	.629	−5
Blairmore..................	1924	.638	.637	1
Cranbrook..................	1924	.716	.716	0
Field..................	1915	.750	.752	−2
Nelson..................	1924	.755	.754	1
Banff..................	1915	.755	.759	−4
Lethbridge*..................	1921	.760	.761	−1
Invermere..................	1925	.767	.768	−1
Princeton..................	1924	.778	.782	−4
Calgary..................	1915	.825	.832	−7
Vernon..................	1925	.906	.905	1
Revelstoke..................	1915	.905	.907	−2
Jasper..................	1924	.932	.931	1
Kamloops..................	1915	.949	.951	−2
Vancouver..................	1915	.952	.954	−2
Vancouver..................	1926	.951	.960	−9
Red Deer..................	1925	.995	.999	−4
Edson..................	1924	981.106	981.100	6
Edmonton*..................	1924	.173	.169	4

*Gravimeter values refer to precise location of pendulum pier.

Means of Differences	With regard to sign (mgal.)	Without regard to sign (mgal.)
1915 stations	−3.1	3.1
1924	0.3	2.5
1925	−1.8	2.3
1926	−9.0	9.0
all	−1.6	3.0

REDUCTION OF OBSERVATIONS

The principal facts for all stations are set out in the appendix, in much the same way as in other recent Dominion Observatory publications. Stations are named according to town, railway station or river crossing, and listed with latitude, longitude, elevation, observed gravity and various types of anomaly. The positions of stations have been scaled from maps of the largest scale available in each case. In many cases these were 1 or 2 miles to 1 inch, but a few stations are located in areas where only 4 mile or even 8 mile to 1 inch mapping is available. Because of the relatively large differences in height involved through the area, the obtaining of reliable elevations for the stations was a considerable problem. In other areas, aneroid barometers have been used, with results accurate to perhaps 5 feet, but the differences of height in the mountains, and the variable pattern of atmospheric pressure conditions, make their use undesirable in this case. Fortunately, sufficient control was obtained from various sources to make it unnecessary to use aneroid barometers except for a very few cases. Along the valleys of the Columbia, Kootenay and Kettle rivers, and their tributaries, use was made of elevations supplied by the Columbia Rivers Survey of the Legal Surveys of this Department. The field work of this Survey had been done in the years immediately preceding the season of the gravity observations, and it was possible to locate many gravity stations at temporary bench marks, as well as permanent monuments, of this organization. This was especially true in the southern part of the Rocky Mountain Trench, where good detail was desired. Over the remainder of the area, stations were located at bench marks of the Geodetic Survey of Canada, or at points of known elevation along railways. The Department of Public Works of British Columbia kindly supplied information from highway profiles in some places.

The only important gap in elevation control was on the highway from Vernon to Needles, over the Monashee Pass. It was necessary to use the aneroid barometer for stations (numbers 223, 224, 225, 227, and 228) along about 60 miles of this line. Fortunately, weather conditions were quite stable at the time these observations were made, and the barometer readings, taken twice at each station, appear quite reliable.

The free air and simple Bouguer anomalies shown in the tables are based on the International Formula for gravity at sea level, with a crustal density of 2.67 grams per cubic centimetre adopted for the Bouguer correction. The designation of the Bouguer anomalies as "simple" is to indicate that no terrain correction has been made.

In a mountainous region such as southern British Columbia, it is of course essential that any detailed interpretation be based on anomalies which are corrected for the topographic effect. It was thought to be worth while also to compute isostatic anomalies on at least one hypothesis, to indicate the degree of compensation existing. The method of computation adopted was that of Bullard (1936), in which the simple Bouguer anomaly is the starting point, and corrections for irregularities of topography, curvature of the earth's surface, and compensation, are applied to it. Mean elevations were read from maps for each of the Hayford zones surrounding a station, out to the limit of zone O, which has an outer radius of 166 kilometres. The topographic correction for each zone depends on the difference in height between that zone and the station. These corrections are conveniently tabulated by Swick (1942), as is the curvature correction, which is a simple function of station height.

The hypothesis of compensation adopted for computing the isostatic anomalies was the Airy-Heiskanen type, with a depth of compensation of 40 kilometres for regions at sea level. This was chosen because that depth is fairly close to the depth of the Mohorovičić discontinuity as determined seismologically by Hodgson (1953) in Northern Ontario, 36 kilometres, and by Milne for the vicinity of Victoria, 33 kilometres (Hodgson, J. H. 1954). The identification of the Mohorovičić discontinuity with the level of compensation is probably as sound a preliminary hypothesis as can be found, and it is felt that the Airy anomalies calculated for the single depth of 40 kilometres will be as useful as any in the interpretation. It is realized that certain recent seismic determinations of the depth of the Mohorovičić discontinuity in mountainous regions are not in accord with this picture of compensation (Tuve and Tatel 1955), but this will be discussed later. To return to the actual computations, the effects of compensation for each zone surrounding a station, to the limits of zone O, were obtained from the tables of Heiskanen

(1938). For the remainder of the earth's crust, beyond the limits of zone O from any station, it is more convenient to estimate the combined effect of topography and compensation. This quantity varies rather slowly from place to place, and it had already been calculated for about 25 Mendenhall pendulum stations in the area by Miller and Hughson (1936). Their calculations of it were plotted on a map which could be contoured smoothly at intervals of one milligal. This map was then used to interpolate the correction at any station at which it was desired.

The greatest labour involved was undoubtedly the estimation of heights of the compartments out of zone O. Contoured topographic maps on a sufficiently large scale were not available for many stations, and a compromise was necessary. Full reductions were therefore made for about one-third of the total number of stations, distributed as uniformly as possible over the area, and for all stations in the region of the Rocky Mountain Trench from Radium south (see Maps 1 and 2). In general, stations were chosen for which maps on a scale of 1 or 2 miles to 1 inch, with contour intervals of less than 100 feet, were available to the limit of zone K (18.8 kilometres) from the station. Compartments in the L, M, and N zones were read on maps of scale 8 miles to 1 inch with contour intervals of 1,000 feet, and elevations in zone O were estimated from 1:1,000,000 charts. It is still possible that the effects of terrain very close to the station have been underestimated by this method, although personal judgment, and the recollection of the local conditions surrounding stations, were used in making the selections.

Some of the stations for which reductions were made coincided with stations of Miller and Hughson, in their study referred to above. It was found that their estimates of height in mountainous regions were consistently high, and the effect of compensation therefore consistently too large. This was traced to the map available at the time of their work, on a scale of 100 miles to 1 inch, which showed large areas of uniformly high elevations. The newer 8 mile maps, based on aerial photographs show that such areas are composed of peaks and valleys, for which the average height is much less than was formerly indicated. Consequently, the isostatic anomalies now tabulated are less in absolute value (by as much as 10 milligals) than those published by Miller and Hughson for the same stations. The point is mentioned here because the same situation may exist in other mountainous regions where corrections were based on small-scale, generalized maps. It is difficult to estimate the error to be expected in the final anomalies in the present case, but it is believed that the total corrections for topography and compensation have been computed to an accuracy of about one milligal. In the case of stations within a particular region, such as the Trench area, the correction for local terrain, which is the important factor in studying the relative values of anomalies over structures of limited extent, is probably a good deal more reliable than this. The magnitude of the terrain correction involved throughout the area studied is indicated by the following distribution table:

		No. of Stations
Terrain Correction	0 – 1 mgal.	20
	1 – 5 mgal.	104
	5 – 10 mgal.	50
	10 + mgal.	29

INTERPRETATION OF THE REGIONAL GRAVITY FIELD

The results of the observations and computations described above for the complete area, are presented in the form of two contour maps. Except in the area of the Rocky Mountain Trench where station density is too great to indicate on this scale, the locations of all stations are shown. Anomalies corresponding to the actual stations are not shown on this map, because it is based largely on the simple Bouguer anomalies, uncorrected for topography. It was felt desirable to construct one map making use of all stations, in order to show most clearly the trend of the anomaly features, and, as explained before, full corrections were made for only one-third of the stations. The application of the topographic correction would not significantly change the form of the 10 milligal contours on this map, although the absolute value of all anomalies would be one or more milligals greater. The second map shows the position of stations for which corrections for topography and compensation were made, with the Airy isostatic anomaly at each station, and contours at 10 milligal intervals. These maps portray the gravitational field over a belt about 600 miles wide across the southern Canadian Cordillera, giving more detail than has been available in these mountains, or for that matter, in most of the North American Cordillera. The distribution of stations, especially those for which full corrections are available, is still such that only for fairly major structures within the belt can an interpretation be attempted.

A preliminary examination of the contour maps shows Bouguer anomalies ranging from -20 to -210 milligals, as might be expected in a mountainous area, with isostatic anomalies between 26 and -27 milligals. One feature of the contours that may be unexpected is their tendency to cut across the mountain structures, which trend northerly or northwesterly across the western part of the map area. In contrast, the contours in the vicinity of the International Boundary strike almost east-west. There is therefore not a simple relation between the gravity field and the distribution of heights, and some outline of the structural history of the region will be required before an interpretation is suggested.

GENERAL DESCRIPTION OF THE AREA

The area under consideration extends from the plains region, east of the foothills through the Rocky Mountains and the western Cordilleran mountains to the shores of the Strait of Georgia, which separates Vancouver Island from the mainland. Thus, while the western limit of the area is at sea level, it is still some 100 miles from the edge of the continent, if the latter is taken as the western shore of Vancouver Island.

The geological structure is markedly different in the eastern and western divisions of the mountains. The true Rocky Mountains, which form the eastern division, lie between the foothills and a line which closely follows, or coincides with, the Rocky Mountain Trench, a feature which will be described in more detail later. These mountains are marked by the almost complete absence of igneous rock, in contrast to the western ranges. They consist of late Precambrian, Palaeozoic and Mesozoic sedimentary rocks, mountain-built during Tertiary time largely through thrust faulting. Many of these faults dip to the west but Evans (1933) and North and Henderson (1954a) have given examples of uplift by wedge action between east- and west-dipping thrusts. The Precambrian rocks within the area considered are exposed along anticlinal structures within the main range of the Rockies, along the headwaters of the Bow River, and near Jasper. Peak elevations within the southern Rocky Mountains are in many places over 10,000 feet.

The western Cordilleran division in southern British Columbia includes from east to west, a series of mountains, the Purcell, Selkirk and Monashee Mountains, a portion of the extensive Interior Plateau, and a part of the Coast Mountains (see Figure 1). Within the Purcell and Selkirk Mountains, in southeastern British Columbia, is found the very thick belt series of late Precambrian rocks, the Purcell and Windermere. Associated with the Purcell sedimentary rocks, which are believed to be over 40,000 feet thick, are numerous basic sills and dykes. The sedimentary rocks are mainly quartzite and argillite. Overlying these is the Windermere system, containing over 20,000 feet of sedimentary rock. Thus the total thickness of late Precambrian sediments in the region is very great, and their deposition must almost certainly have been accompanied by major crustal flexure to produce geosynclinal conditions.

West of the area of Precambrian rocks, large areas are occupied by batholithic intrusive masses, of Jurassic or Cretaceous age. The rocks, known as the Coast intrusions, are of variable composition, but the average type is probably a granodiorite. The largest exposure, which forms the core of the Coast Mountains, lies to the north of the area under study, but batholiths of apparently related rocks occur to the west of Okanagan Lake, and in the vicinity of Nelson. These and other exposures are indicated on the Bouguer and isostatic anomaly maps. The rocks intruded by the Coast batholiths consist of sedimentary and volcanic rocks ranging in age from Carboniferous to Lower Cretaceous. In some areas, including a belt lying to the east of Okanagan Lake and extending to the north of Shuswap Lake, the rocks are metamorphosed and granitized to such an extent that their original nature and age is doubtful. These rocks were originally believed to be Precambrian (the Shuswap series) because of their high degree of metamorphism, but this correlation is now admitted to be uncertain. In part these rocks underly the physiographic division known as the Interior Plateau, where the average elevation is some 4,000 feet above sea level. In the Coast range to the west, and the Selkirk Mountains to the east, peaks range in height up to 12,000 feet.

Deposits of Tertiary age, including volcanic flows, occur in the western part of the area, especially in, and west of, the Okanagan valley. The volcanic rocks reach a few thousand feet in thickness in some places. These formations obscure the older structure, as does the cover of glacial and recent unconsolidated material, which is especially heavy in some of the river valleys.

The western mountains were apparently formed during the time of emplacement of the Coast batholithic rocks, in Jurassic or early Cretaceous time. During the Tertiary period, considerable vulcanism occurred, and many of the older formations are concealed by flows of this age. It was during Tertiary time also, that the Rocky Mountains to the east were formed (Warren 1938), so that these are younger than the western ranges.

Looking at the mountain structure in a still broader way, the Coast range forms one of the primary volcanic arcs of a chain down western North America (Wilson 1954), while the Rocky Mountains form one of the secondary arcs. The latter are characterized by the absence of volcanic rocks, and by thick series of normal sediments. In this classification, the Interior Plateau becomes the Zwischengebirge or median land between the primary and secondary arcs. It is noteworthy also that Wilson defines two topographic lineaments, radiating from the junction of primary arcs near the International Boundary. One of these is marked by the Fraser valley, the other strikes southeasterly into Montana, and is called the Montana or Olympic-Wallowa (Raisz 1945) lineament. Scheidegger (1953) has put forth an explanation for such lineaments radiating from junctions, on the basis of material in the mantle moving along neighbouring arcs.

The foregoing outline of the area under study is very much generalized and abbreviated, but the investigation that can be made over most of the area is generalized also. Further descriptions of geological structures will be given when particular features of the anomaly maps are dealt with.

ROCK DENSITIES

The results of density measurements on samples collected from the area under study are given in Table IV. In many cases it is difficult to know whether or not a measurement is representative of a formation or lithologic unit as a whole, because of variations both stratigraphically and areally within these units. However, certain general conclusions can be drawn. The mean density of the Lower Purcell sedimentary rocks is 2.74 gms. per cc., but these rocks are interbedded with the Purcell extrusives, and intruded by the Purcell intrusives, so that a section of Lower Purcell may well have a density close to 2.80 gms. per cc. The samples from the Windermere series average 2.71 gms. per cc., from the Palaeozoic rocks of the Rocky Mountains 2.73 gms. per cc., and from the Mesozoic sedimentary and volcanic rocks 2.77 gms. per cc. It would appear, therefore, that the average crustal density in the region, exclusive of the granitic rocks, is close to 2.74 gms. per cc. The latter appear to be definitely less dense than the formations by which they are surrounded, as the mean density of the Nelson or Coast "granites" is 2.63 gms. per cc. There is a variation in density among samples even from the same locality, as might be expected in view of the gradation in rock type from granite through granodiorite. In general, the coarser-grained phases of the granitic rocks have the lower densities. These phases would correspond to the "red granodiorite" of Rice (1947), which occupies the major portion of the Osprey Lake body west of the Okanagan trench. Rice describes also a "grey granodiorite" which occurs near the southern margin of the same body, and which corresponds to the denser samples. His analyses for the two types are as follows:

Assumed Mineral Density		Red Granodiorite (Osprey Lake)	Grey Granodiorite
2.65	Quartz	20.2%	21.8%
2.67	Plagioclase	47.6	59.8
2.57	Potash Feldspar	25.1	4.4
3.00	Ferromagnesian and accessory minerals	7.1	14.0
	Per cent An of Plagioclase	*27*	*30*
	Theoretical density	2.66	2.71

Rice remarks that the grey granodiorite "may be the result of widespread granitization with little introduction of molten magmatic material". The fact that the theoretical density of this phase is close to the mean measured density of the older rocks would support this suggestion. The lower density of the coarse-grained red phase appears to result from a real difference in composition, specifically a decreased ferromagnesian and increased potash feldspar content.

As working values for density differences, we may take 0.10 gm. per cc. as the density deficiency of the main bodies of granite, and 0.05 gms. per cc. as the density excess of sections of Lower Purcell rocks containing basic extrusive and intrusive types. Both of these figures are relative to a "normal" density of about 2.73 gms. per cc. for the other rock types. The relatively low density (2.26 gms. per cc.) of samples of primary gypsum from the Kootenay valley is also noteworthy, and reference will be made to this when more local effects are discussed.

THE REGIONAL GRAVITY FIELD

The main feature of the Bouguer anomaly map is, of course, the minimum, reaching −200 milligals, centred over the interior ranges. To the east, over the plains, the level of Bouguer anomaly rises to about −50 milligals, and similar values occur on the coast near Vancouver. A negative Bouguer anomaly of this order is to be expected over mountain ranges if compensation is present; the immediate question is the nature of the mass deficiency. Two general hypotheses are possible, involving either density variations within the crust beneath the mountains, or variations in the thickness of the crust itself. The fact that the minimum is most intense over the Selkirk and Purcell mountains in the vicinity of granitic batholiths, together with the measured density deficiency of the granite, and the association of negative anomalies with granites in many other areas (Bott 1953), might suggest an interpretation of the entire negative anomaly in terms of a concentration of granite within the crust. If we suppose the "normal" continental crust to consist of material of density 2.73 gm. per cc. (with compressional and transverse elastic wave velocities appropriate to the crust), then a prism of granite of density 2.63 gm. per cc., extending to the base of the crust, would produce a negative anomaly of 150 milligals, if the prism had a horizontal extent more than a few times its thickness. In other words, the major relief of the Bouguer gravity field could be explained in this way, without the assumption of variations in crustal thickness. The surface exposures of the Coast granites cover a very considerable area, as a glance at the geological map of Canada will show, and the above interpretation would not involve a vertical dimension out of proportion to the horizontal extent of the bodies. Furthermore, the findings of Tuve and Tatel (1955) on the thickness of the crust as measured seismologically, have suggested that in some mountain regions the Mohorovičić discontinuity is not depressed as would be expected on an Airy type of compensation. However, there appear to be two reasons why this interpretation is less attractive than one involving variations in crustal thickness. If we consider the form of an anomaly profile taken across the mountain structure, as shown in Figure 4 (see also Figure 1), the gradual decrease into the minimum on the east side is apparent. On the assumption that the main anomaly is due to a large concentration of granite, this would suggest that the eastern boundary of the granite dips easterly (the computed curve shown on the profile is for a dip of 7°), from the most easterly surface exposure. A principal characteristic of the Coast type intrusions in the southern Canadian Cordillera is the abrupt termination of

TABLE IV

DENSITIES OF ROCK SAMPLES

Age	Rock Type or Formation	Locality	Density gm/cc.	Mean gm/cc.
Precambrian	Lower Purcell:			
	argillaceous quartzite	St. Mary River	2.69	
	chlorite schist	Wildhorse River	2.74	2.74 (Lower Purcell sedimentary rocks)
	quartzite	Luster River	2.84	
	slate	Luster River	2.68	
	amygdaloidal lava	Skookumchuck	2.84	
	Upper Purcell:			
	altered lava	Findlay Creek	2.47	
	quartzite	Paradise Mine	2.63	
	slate	Paradise Mine	2.64	
	Hector:			
	slate and conglomerate	Lake Louise	2.74	
	Windermere:			
	chlorite schist	Lardeau River	2.95	
	quartzite	Lardeau River	2.61	
	conglomerate	Horsethief Creek	2.64	2.71
	schist	Horsethief Creek	2.77	
	slate	Lake Windermere	2.69	
Precambrian or younger	Shuswap complex:			
	gneiss	Revelstoke	2.82	
Cambrian	quartzite	Jasper	2.69	
	slate	Jasper	2.80	2.73 (Rocky Mountain Palaeozoic samples)
	quartzite	Sunwapta Pass	2.83	
	Cathedral: limestone	Kicking Horse Pass	2.71	
	Eldor: limestone	Kicking Horse Pass	2.74	
Devonian	limestone	Rocky Mountain foothills	2.68	
	gypsum	Kootenay River	2.26	
Mississippian	Banff: shaly limestone	Rocky Mountain foothills	2.66	
Carboniferous	sheared basic volcanic	Vernon	2.67	
Triassic	basic volcanic	Nicola Lake	2.95	2.77 (Mesozoic volcanic and sedimentary rocks)
	basic volcanic	Princeton	2.82	
Lower Cretaceous	Agglomerate	Spence's Bridge	2.70	
	andesite	Spence's Bridge	2.74	
	conglomerate	Nicola River	2.66	
Jurassic or Cretaceous	Nelson granite:			
		Slocan Lake	2.62	
		Slocan Lake	2.54	
		Slocan Lake	2.72	
		Lower Arrow Lake	2.68	2.63 (Nelson and Coast type granitic rocks)
		Granby River	2.53	
	Coast intrusives:			
	gneissic granite	Yale	2.59	
	granite	Osprey Lake	2.65	
	porphyritic granite	Osprey Lake	2.68	
	granite	Shuswap Lake	2.63	
Tertiary	sandstone	Kettle Valley	2.43	
	shale	Kettle Valley	2.40	
	lava	Kamloops	2.18	

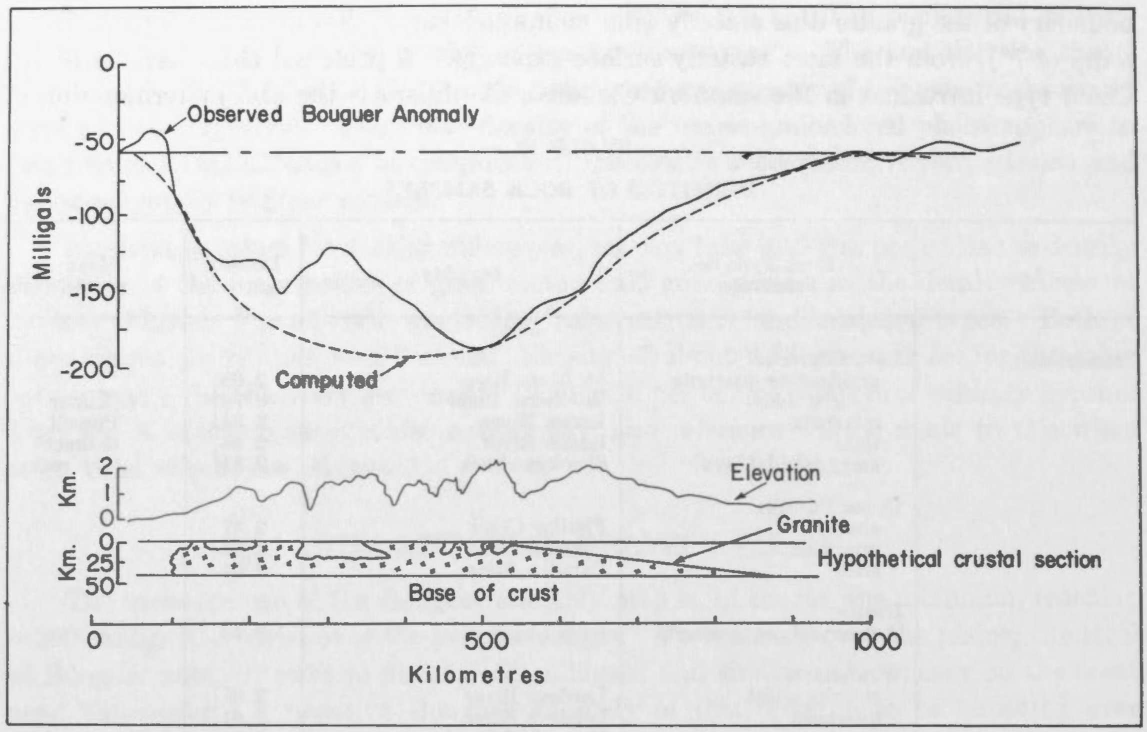


FIGURE 4. Bouguer anomaly profile across the southern Canadian Cordilleras. The cross-section indicates the form of a low-density body within the crust which would account for the main mass deficiency. The hypothetical body is extended in strike, with a sloping eastern boundary and steep western boundary.

exposures at the eastern boundary of the Purcell mountains. No exposures are known in the Rocky Mountains or east of them, yet the structure shown in Figure 4 places granite at a fairly moderate depth beneath the Rocky Mountains. It will be seen from the profile that regions of older rock between the Nelson, Okanagan, and Coast batholiths, with which are associated higher values of Bouguer anomaly, are, on this interpretation, in the forms of roof pendants, underlain by granite. At the extreme westerly end of the profile, the contact of the granite with normal crustal rocks would have to be steeply dipping.

The second objection to the above interpretation is of a more general nature: the origin of such a large volume of rock consistently less dense than the crust as a whole is difficult to explain. If the prism of lighter granite is assumed to result from a separation of the lighter minerals of the crust, it is not apparent where the heavier fraction could be, since it is necessary to have the granite extending to the base of the crust. However, it would be possible to argue that the original base of the crust had been depressed during mountain building, and that the denser fraction of a differentiated section of crust filled the lower portion of the downfold.

Because of the horizontal extent of the area, the positive and negative attractions of the heavy and light fractions cancel, and the negative anomaly must be largely explained by the crustal thickening. Hence we are led to the second form of interpretation, involving distortions at the base of the crust.

It is to be noted that seismological observations might indicate the top of the denser fraction to be the Mohorovičić discontinuity, if the boundary was sufficiently sharp, as has been suggested by van Bemmelen (1952). If this were so, it could reconcile the findings of Tuve and Tatel in certain mountainous areas with the notion of root formation and compensation.

On the other hand we may begin the interpretation with the assumption that the base of the crust has been warped in accordance with an Airy form of compensation. We then attribute the larger part of the negative Bouguer anomaly to this warping, and only the much smaller isostatic anomalies are to be explained in terms of anomalous densities, or departures from the Airy crust. Until more specific information is available on the depth of the Mohorovičić discontinuity in the area, it seems reasonable to proceed with the interpretation on this hypothesis. It will be seen from the isostatic anomaly map that the areas of granite are characterized by negative anomalies reaching about 30 milligals. These could be explained by assuming the granite extends to depth beneath the surface outcrops, to about 7 kilometres, or one-fifth of the thickness of the crust. Such an interpretation is shown in Figure 5 (see also Figure 1), where it will be seen that the amount of granite involved is very much less than in the previous interpretation. However, because of the width of the exposures of granite (up to 100 kilometres), there remains the difficulty of accounting for the anomalies if any form of differentiation, or increasing density with depth, is assumed. For example, consider a prism of original crust (density 2.73) of 100 kilometres width and considerable length, to separate by some process into

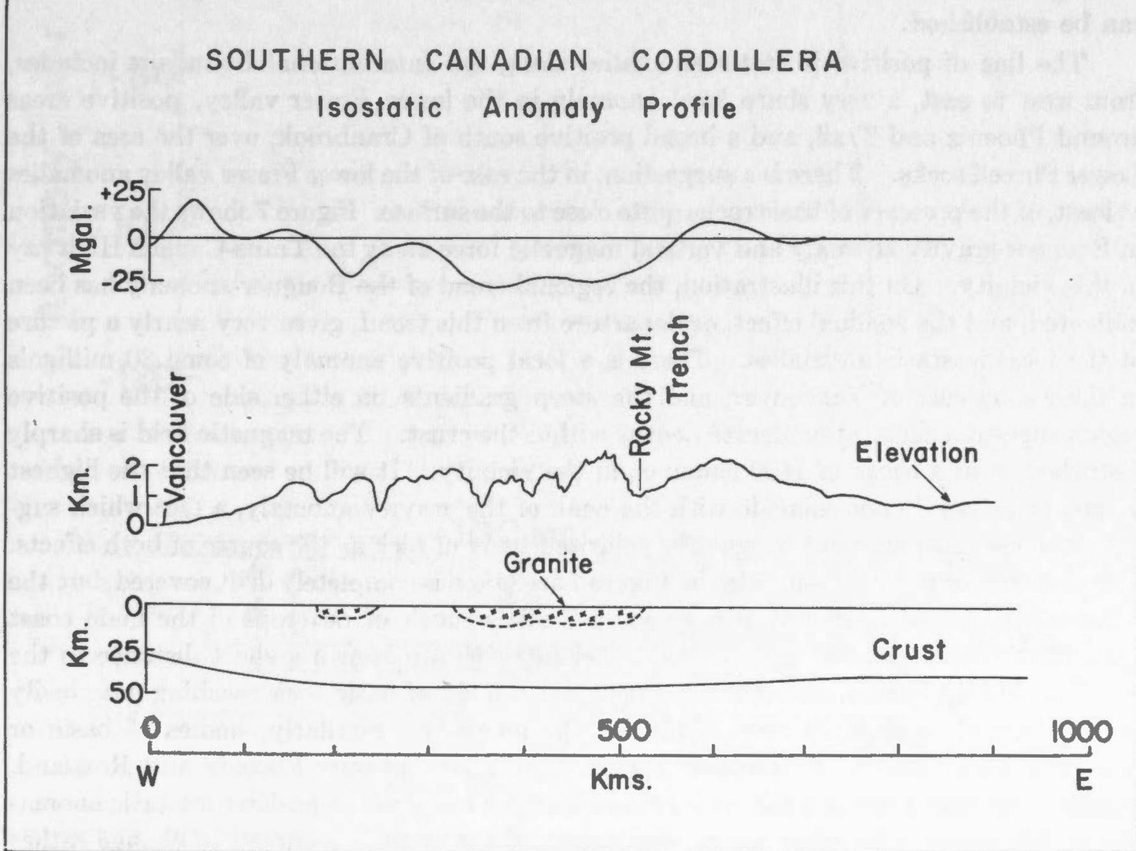


Figure 5. Isostatic anomaly profile across the southern Canadian Cordillera. The cross-section indicates the thickening of the Airy crust beneath the elevated regions and the form of granitic batholiths which would account for the negative isostatic anomalies.

an upper, granitic portion of density 2.63, and a lower, basic portion. Because of the width of the prism relative to its vertical dimension, the positive attraction of the lower fraction very greatly diminishes the negative anomaly due to the upper portion. The variation of resultant anomaly with thickness of prism is shown in Figure 6, and from this we find that a negative anomaly of greater amplitude than 20 milligals implies a further depression of the base of the crust, beneath that required for compensation, to accommodate the denser fraction. Since the anomalies observed over the batholiths of the interior mountains reach -30 milligals, it would appear that either there is such a depression, or the lighter granitic rocks in these ranges have been formed by some process independent of the settling of the denser constituents.

On the second form of interpretation the granite is assumed to underly chiefly the areas of surface outcrop, or other areas of negative isostatic anomaly, in contrast to the first hypothesis where it would be assumed to underly all the region of abnormally negative Bouguer anomaly, concealed by abundant roof pendants. In the second case, therefore, the area underlain by granite must be interrupted rather abruptly along the International Boundary, where the anomaly contours trend east-west and the isostatic anomaly rises sharply to positive values. The area of granite development appears to swing from the Coast batholith southeasterly through the Nelson batholith, then northerly under the Selkirk and Purcell mountains toward the Big Bend of the Columbia River. North of the Big Bend, more observations are required before the trend of the negative anomaly can be established.

The line of positive isostatic anomalies along the International Boundary includes, from west to east, a very sharp local anomaly in the lower Fraser valley, positive areas around Phoenix and Trail, and a broad positive south of Cranbrook, over the area of the Lower Purcell rocks. There is a suggestion, in the case of the lower Fraser valley anomalies at least, of the presence of basic rocks quite close to the surface. Figure 7 shows the variation in Bouguer gravity anomaly and vertical magnetic force along the Trans-Canada Highway in this vicinity. On this illustration, the regional trend of the Bouguer anomaly has been indicated, and the residual effect, or departure from this trend, gives very nearly a picture of the local isostatic anomalies. There is a local positive anomaly of some 30 milligals in the region east of Vancouver, and the steep gradients on either side of the positive region suggest a cause at moderate depths within the crust. The magnetic field is sharply disturbed, over a range of 1400 gammas, in the vicinity. It will be seen that the highest magnetic values do not coincide with the peak of the gravity anomaly, a fact which suggests a dense, magnetic but irregularly polarized body of rock as the source of both effects. The area across which the profiles of Figure 7 are taken is completely drift covered, but the remarkable feature is that it is only some 5 miles south of outcrops of the main coast batholith. Basic rocks of Cretaceous or Tertiary age are known a short distance to the south on Mount Sumas, and it is supposed that a body of basic rock reaching practically to the bedrock surface, is responsible for the anomaly. Similarly, bodies of basic or ultrabasic rock, mostly of Mesozoic age, in the region between Phoenix and Rossland, suggest a concentration of basic rock in the crust as a cause of the positive iosstatic anomalies in this region. In other words, the nature of the crust is assumed to change rather abruptly from granitic to basic as the International Boundary is approached, giving rise to the pattern of anomaly contours cutting across the mountain structure.

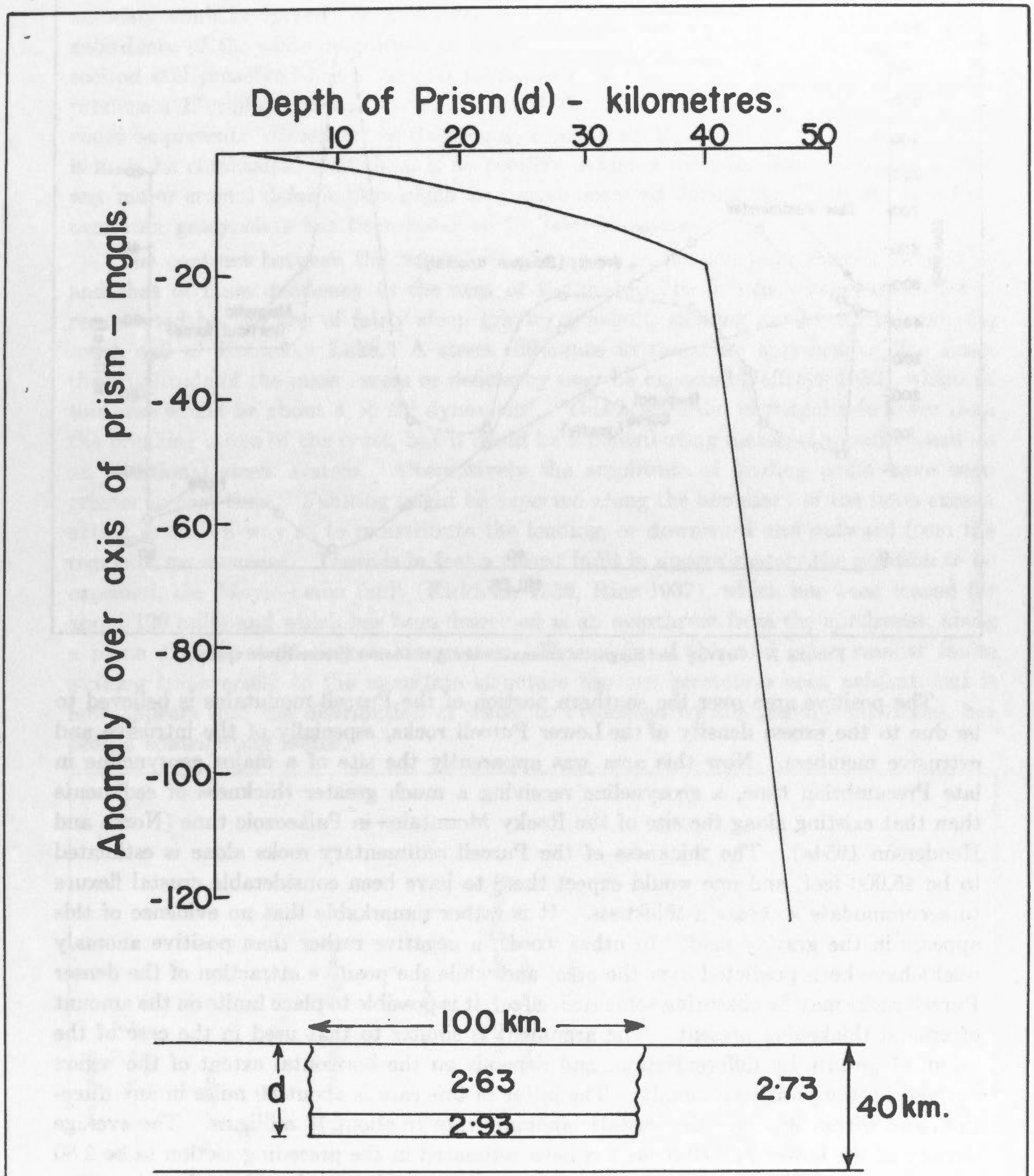


FIGURE 6. Calculated anomaly to be observed over a differentiated prism of rock within the crust. The original density of the prism is taken to be that of the crust, while the densities after separation are as indicated.

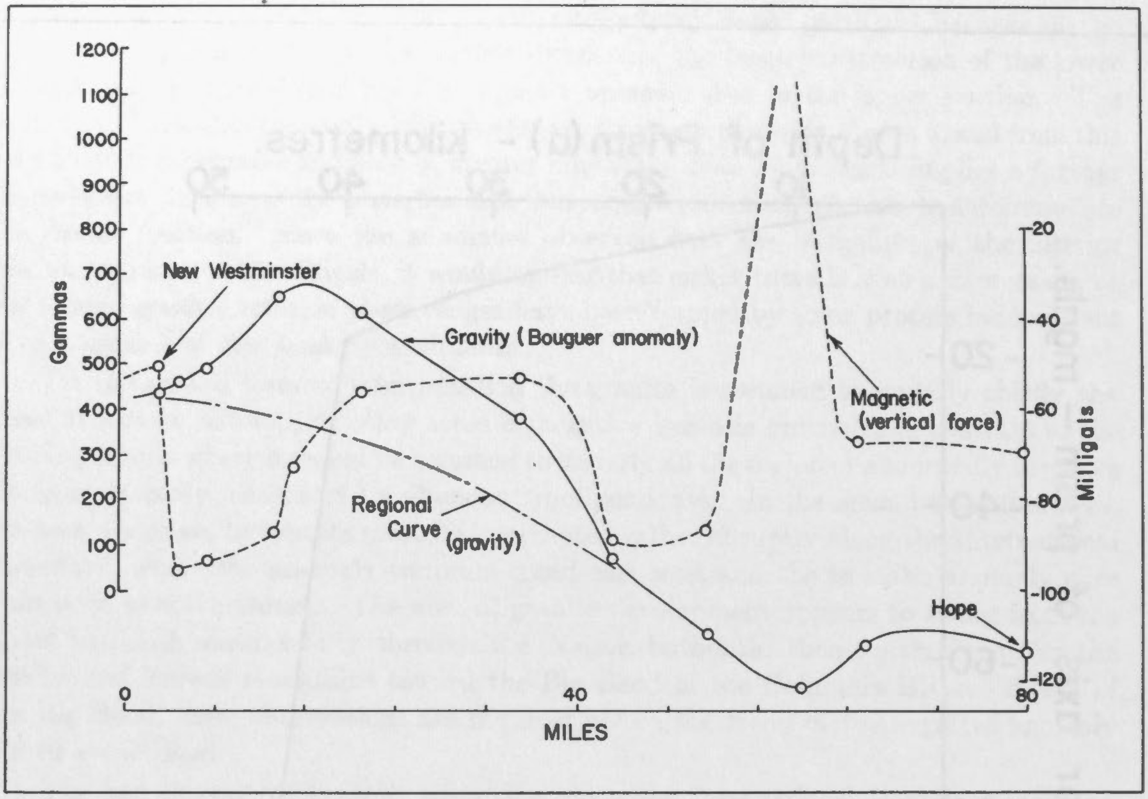


FIGURE 7. Gravity and magnetic anomalies along the lower Fraser River valley.

The positive area over the southern portion of the Purcell mountains is believed to be due to the excess density of the Lower Purcell rocks, especially of the intrusive and extrusive members. Now this area was apparently the site of a major geosyncline in late Precambrian time, a geosyncline receiving a much greater thickness of sediments than that existing along the site of the Rocky Mountains in Palaeozoic time (North and Henderson 1954a). The thickness of the Purcell sedimentary rocks alone is estimated to be 45,000 feet, and one would expect there to have been considerable crustal flexure to accommodate so great a thickness. It is rather remarkable that no evidence of this appears in the gravity field. In other words, a negative rather than positive anomaly might have been predicted over the area, and while the positive attraction of the denser Purcell rocks may be obscuring some such effect, it is possible to place limits on the amount of crustal thickening present. The argument is similar to that used in the case of the origin of granite by differentiation, and depends on the horizontal extent of the region covered by the positive anomaly. The latter in this case is about 80 miles in any direction, and within this area the isostatic anomaly rises to about 17 milligals. The average density of the Lower Purcell rocks has been estimated in the preceding section to be 2.80 gms. per cc., or 0.07 gms. per cc. greater than the normal crust, based on the proportion of basic flows and sills present in the section. Thus, each kilometre thickness of Lower Purcell would contribute about 2.9 milligals to the positive anomaly. On the other hand, subsidence at the base of the Airy crust, over a circle of 80 mile diameter, would contribute a negative anomaly approaching 20 milligals per kilometre of subsidence, for a density contrast of 0.5 gm. per cc. at the base of the crust, and of course this negative anomaly would be spread over a broader area. It is apparent that there cannot be crustal subsidence of the same magnitude as the thickness of the section. If the Lower Purcell section still preserved has a vertical thickness greater than the 19,000 feet required to produce a 17-milligal anomaly then a crust thicker than that required for compensation could be present. However the thickening is not likely to exceed 3 or 4 kilometres, and it must be emphasized that there is no positive evidence even for this. It appears that any major crustal deformation which may have occurred during the life of the late Precambrian geosyncline has been removed by later orogenies.

The contract between the region of excess mass in the southern Purcell mountains and that of mass deficiency in the area of the granitic batholiths to the northwest is represented by the line of fairly steep gravity gradient, striking northeasterly from the south end of Kootenay Lake. A stress difference in the crust approaching 2/e times the amplitude of the mass excess or deficiency may be expected (Jeffreys 1952), which in this case would be about 4×10^7 dynes/cm². This is an order of magnitude lower than the breaking stress of the crust, but it could be a contributing factor, if superimposed on an additional stress system. Alternatively the amplitude of loading could have been greater in past time. Faulting might be expected along the boundary of the mass excess, acting in such a way as to redistribute the loading, or downward and outward from the region of mass excess. There is in fact a thrust fault in approximately the position to be expected, the Moyie-Lenia fault (Kirkham 1930, Rice 1937), which has been traced for about 120 miles and which has been described as an overthrust from the northwest, along a plane dipping at 45 degrees or greater. The origin of this and other smaller faults striking transversely to the mountain structure has not heretofore been evident, but it now appears that the distribution of loads, as evidenced by the gravity anomalies, has been a contributing factor.

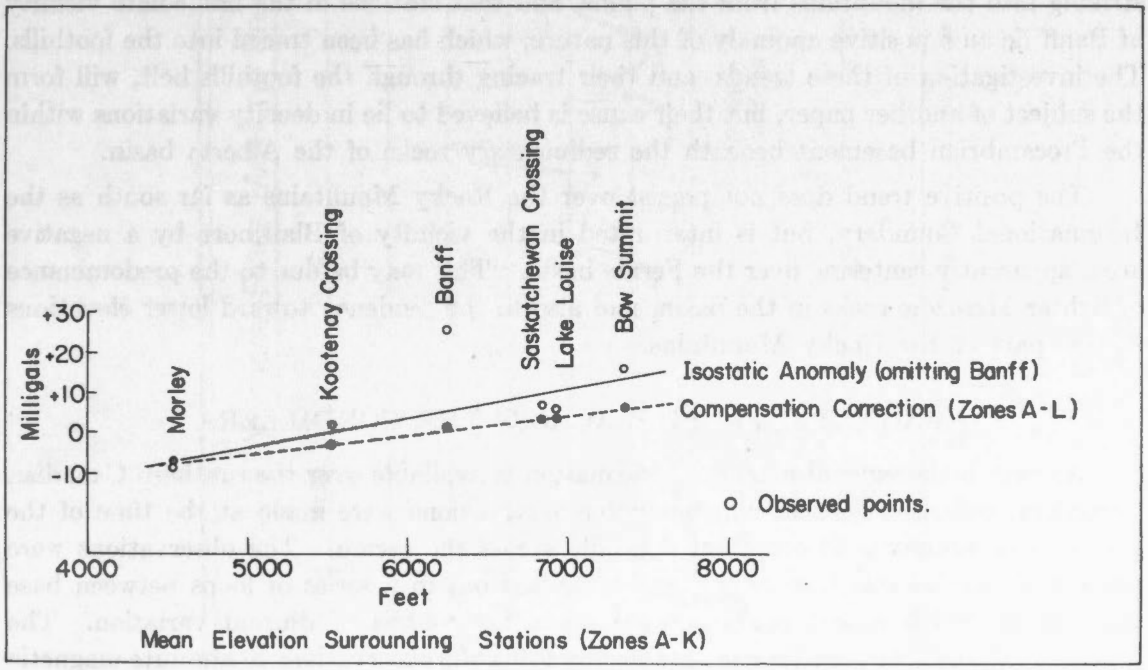


FIGURE 8. Variation of isostatic anomaly with height for stations in the Rocky Mountains in the general vicinity of Banff.

The pattern of anomalies over the Rocky Mountains themselves is interesting. These mountains, although of a comparable elevation to the interior mountains to the west, lie on the eastern shoulder of the main area of highly negative anomaly, and it is not surprising that the isostatic anomalies over them show a tendency toward positive values. The positive trend is most pronounced in the vicinity of Banff, and suggests an incomplete compensation of the topography in the region. The relation between isostatic anomaly and the mean height of the topography surrounding a station (taken to the limit of zone K, or to 18.8 kilometers) is shown in Figure 8, for six stations in this section of the Rocky Mountains. The isostatic anomaly increases in a general way with height, the major part of the increase being provided by the correction added for compensation out to zone L, or to 28.8 kilometres from each station. This suggests that the topography above about 4,500 feet, in this portion of the Rocky Mountains, is not completely compensated. In other words, it would appear that the crust having adjusted itself at the time the Coast and interior ranges were formed, did not suffer further major distortion when the Rocky Mountains were built by overthrusting or wedge-faulting of the sedimentary rocks. Otherwise, it would be difficult to reconcile the tendency toward positive isostatic anomalies, suggesting a crust thinner than that called for by Airy compensation, with the very large estimates of crustal shortening that have been based on geological evidence. For example, North and Henderson (1954a), estimate 100 miles or 50 per cent of the original width as the shortening across the Rocky Mountains and the Trench, a figure which must almost certainly apply to a relatively thin surface layer, and not to the crust as a whole.

Referring again to Figure 8, it will be seen that the anomaly at Banff lies very much above the line through the other points. Hence this station must be affected by some factor in addition to the apparent under-compensation. We believe there are anomaly trends striking into the mountains from the plains, and that stations in the immediate vicinity of Banff lie on a positive anomaly of this nature, which has been traced into the foothills. The investigation of these trends, and their tracing through the foothills belt, will form the subject of another paper, but their cause is believed to lie in density variations within the Precambrian basement beneath the sedimentary rocks of the Alberta basin.

The positive trend does not persist over the Rocky Mountains as far south as the International Boundary, but is interrupted in the vicinity of Blairmore by a negative area, apparently centering over the Fernie basin. This may be due to the predominance of lighter Mesozoic rocks in the basin, and also to the tendency toward lower elevations in this part of the Rocky Mountains.

MAGNETIC PROFILE ACROSS THE CORDILLERA

As very little regional magnetic information is available over the southern Canadian Cordillera, sufficient vertical magnetometer ovservations were made at the time of the gravity measurements to construct a profile across the region. The observations were made with an Askania instrument, and were laid out in a series of loops between base stations, at which repeat readings were made for control of diurnal variation. The absolute datum for the profile was obtained by tying the observations to absolute magnetic stations at Fort McLeod, Cranbrook and Midway. In Figure 9, the profile is shown pro-

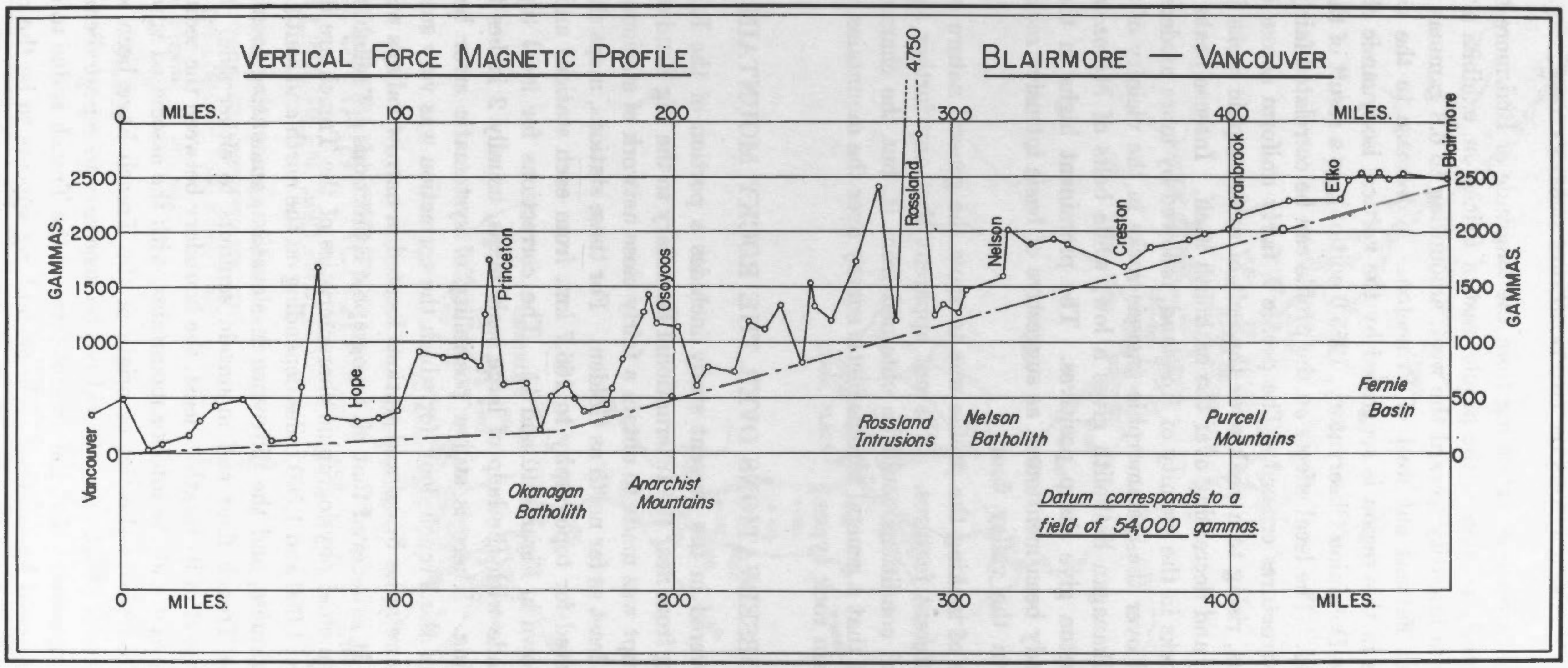


FIGURE 9. Vertical force magnetic profile from Blairmore, Alberta, to Vancouver, B.C.

jected onto an east-west line, extending from the longitude of Blairmore to that of Vancouver. The easterly portion of the profile, east of Princeton, exhibits a rather uniform regional decrease in intensity toward the west, amounting to 6.8 gammas per mile, while the regional effect flattens out west of Princeton. A decrease to the west of about 7 gammas per mile in this region is suggested by the vertical isodynamic chart of Canada (published by the Dominion Observatory, 1955.0 edition), as a result of the configuration of the earth's field. The local effects on the profile can be correlated fairly well with the main geological structures crossed. The profile is fairly uniform across the Rocky and Purcell mountains, rising to a peak over the belt of metamorphic rocks just east of the Nelson batholith, and decreasing over the batholith itself. Intense peaks occur over the basic intrusive rocks in the vicinity of Rossland, followed by more moderate values until a high is reached over the metamorphic gneissic rocks in the vicinity of Osoyoos. The interior of the Okanagan batholith gives a low, while belts of Mesozoic and Tertiary lavas near Princeton give sharp positives. The prominent highs in the lower Fraser valley have already been mentioned, as suggestive of basic intrusive rock lying beneath the overburden in the valley floor.

The purpose of making the profile was to show the general nature of the magnetic field over the different features. It is not apparent that any further significant information on crustal conditions could be obtained from it, but the characteristics of the profile do suggest that a general aeromagnetic survey over the mountains would be useful in outlining certain rock types.

GRAVITY OBSERVATIONS OVER THE ROCKY MOUNTAIN TRENCH

The area covered in the present study includes a portion of the Rocky Mountain Trench, extending from near the International Boundary to the Big Bend of the Columbia River. An attempt was made to obtain a fairly close network of stations in the vicinity of the Trench, at least as far north as Golden. For these stations, maps showing Bouguer anomalies (corrected for topography to 166.7 km. from each station) and Airy isostatic anomalies are shown in Figures 10 and 11. The corrections for local topography were practically all made with the help of large scale maps, usually 2 inches to 1 mile, with detailed contouring. There is still a possibility of systematic error between stations near the middle of the Trench floor, for which the correction was very small (the Trench being 4 to 8 or more miles broad and stations located in narrow valleys within the ranges on either side). It is believed that all topographic corrections are reliable to better than one milligal. The chief physiographic characteristics of the Trench are its great length, estimated between 1,000 and 1,500 miles depending on the north and south limits adopted, its relative straightness, and the difference in elevation, amounting to several thousand feet, between the Trench floor and mountain summits to either side. Structurally, it forms, for a large part of its length at least, the boundary between the sedimentary Rocky Mountains to the east and the interior mountains, with the associated igneous intrusives, to the west. The various theories of origin of the Trench have been summarized by North and Henderson (1954b) and it will not be necessary to repeat them in detail here. There is general agreement that the present form of the Trench is due to erosion along a zone or zones weakened by faulting. Thrust faulting appears to be the most important

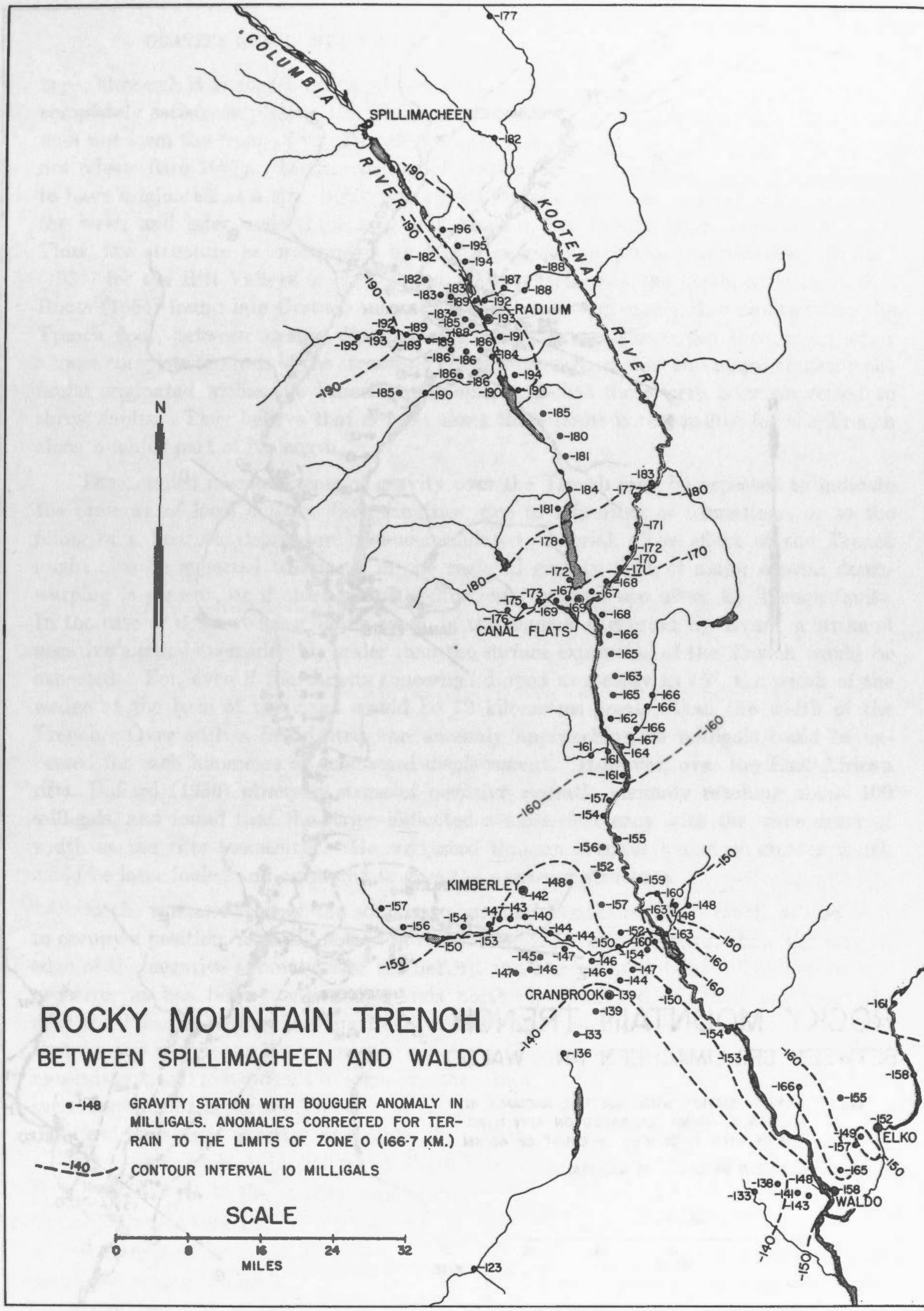


Figure 10. Bouguer anomalies observed over the southern portion of the Rocky Mountain Trench in Canada.

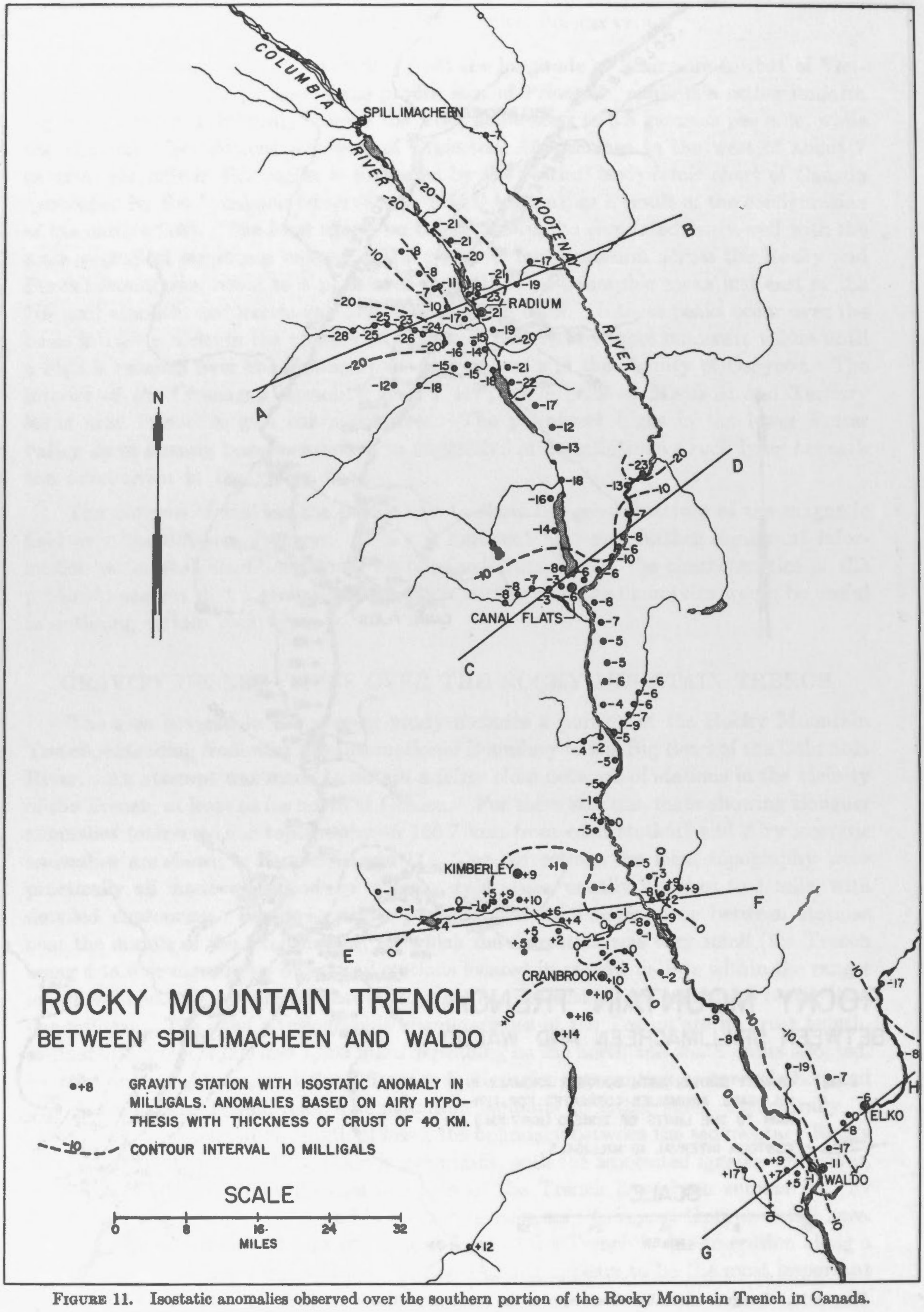


Figure 11. Isostatic anomalies observed over the southern portion of the Rocky Mountain Trench in Canada.

type, although it is characteristic of the Trench that no one structural interpretation is completely satisfactory along the whole length. Thus, south of Canal Flat, the Trench does not form the front of the Purcell mountains, and structures on either side of it are not offset (Rice 1937). In the vicinity of Golden, Evans (1932) considered the Trench to have originated as a structurally depressed area between westerly dipping thrusts on the west, and later underthrusts dipping beneath the Rocky Mountains to the east. Thus, the structure as interpreted by Evans is not unlike that suggested by Bullard (1936) for the Rift Valleys of East Africa. Much farther to the north, at latitude 57°, Roots (1954) found late Cretaceous or Paleocene rocks apparently downfaulted into the Trench floor, between steeply dipping faults. North and Henderson themselves, after a most complete analysis of the structural conditions, suggest that two major transcurrent faults originated within the Purcell mountains, and that these were later converted to thrust faults. They believe that erosion along these faults is responsible for the Trench along a major part of its length.

The detailed measurements of gravity over the Trench may be expected to indicate the presence of local density discontinuities, due to infaulting of formations, or to the filling of a bedrock depression by unconsolidated material. The effect of the Trench might also be expected to appear in the regional gravity field, if major crustal down-warping is present, or if older anomaly-producing features are offset by Trench faults. In the case of downwedging of the crust, in the manner suggested by Evans a strike of negative anomaly considerably wider than the surface expression of the Trench would be expected. For, even if the thrusts concerned dipped as steeply as 45°, the width of the wedge at the base of the crust would be 72 kilometres greater than the width of the Trench. Over such a broad strip, an anomaly approaching 20 milligals could be expected for each kilometre of downward displacement. However, over the East African rifts, Bullard (1936) observed strips of negative isostatic anomaly reaching about 100 milligals, and found that the strips indicated a mass deficiency with the same order of width as the rifts themselves. He suggested that an original wedge of greater width could be later folded and crumpled to give the narrower structure.

On the isostatic map of the southern Canadian Cordillera, the Trench will be seen to occupy a position, from the source of the Columbia River northward, along the eastern edge of the negative anomaly over the Selkirk and Purcell mountains. The axis of this negative, as has been mentioned, trends northerly from Nelson, then northwesterly near the Purcell front to the Big Bend of the Columbia and beyond. The problem is that control within the Purcell mountains north of Spillimacheen (Figure 11) is practically non-existent, and it is difficult to argue whether the axis of the negative anomaly is within the mountains or along the Trench. A single station, shown on the isostatic map in the middle of the area in question, with anomaly −10 milligals, is actually a pendulum station (Glacier) observed in 1915, for which there is no modern check on the observed value. It is felt that while the gravity minimum appears to follow the Trench toward Boat Encampment (where the isostatic anomaly is −32 milligals), the cause of the anomaly is that suggested before, the density deficiency in exposed or concealed granitic rocks developed within the interior mountains. In this regard, a gravity and magnetic profile along the Trench, between Golden and Boat Encampment (Figure 12 and also Map 1 and

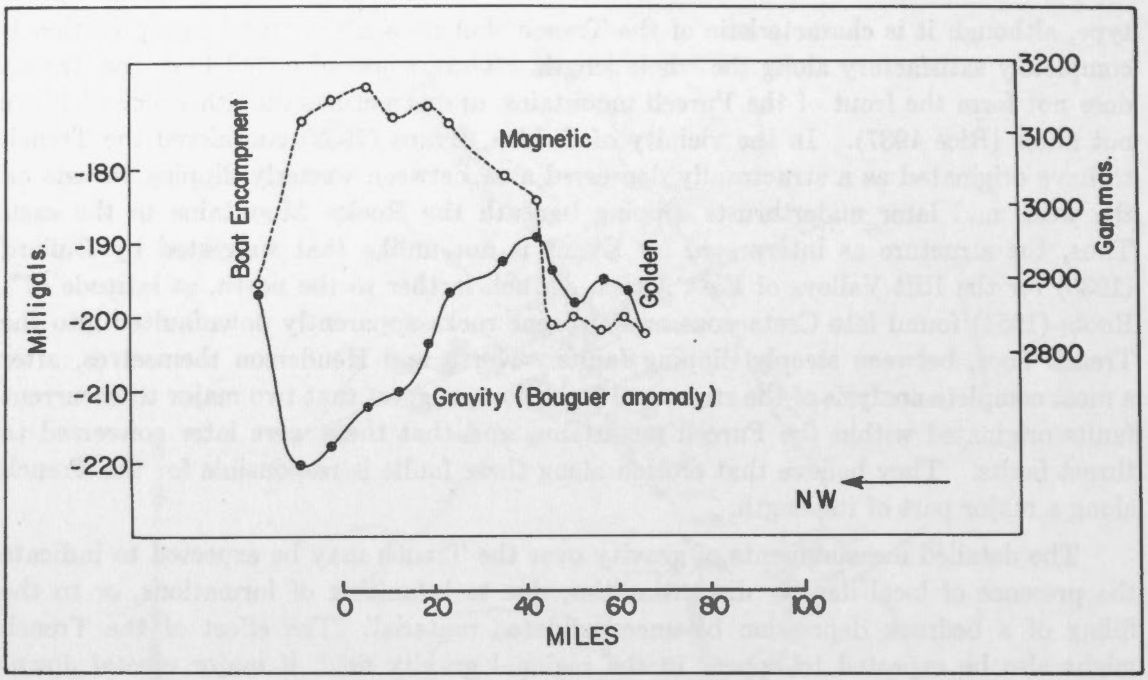


FIGURE 12. Gravity and magnetic profiles along the Rocky Mountain Trench between Golden and Boat Encampment. The latter station is at the northern extremity of the Big Bend of the Columbia River.

2) is illuminating. The Bouguer gravity anomaly shows a relief of 30 milligals, reaching a minimum just south of Boat Encampment. The relief in this profile, taken along the strike of the Trench, is not suggestive of a crustal structure elongated in the Trench direction, and the gravity gradients indicate density differences close to the surface. Furthermore, the magnetic profile indicates a positive anomaly of some 300 gammas over the region of negative gravity. Now the interior of the larger granitic batholiths have been seen to be fairly non-magnetic, but the zones of mixed and metamorphosed rocks around the edges of the batholiths can be highly magnetic, as evidenced by the eastern edge of the Nelson batholith on the main magnetic traverse (Figure 9). It is concluded that a fairly small batholith of the Coast intrusion family underlies the area very close to the Purcell front, in the vicinity of the Big Bend. As will be seen on the map, no intrusions are mapped in this area, although small exposures are known a short distance to the west. On this interpretation, there remains no strong suggestion of down-wedging along the Trench, although the possibility is by no means eliminated.

For more detailed study, isostatic anomaly profiles are shown in Figure 13. Of these, the first two, taken in the vicinity of Radium and Canal Flat, cross the Trench where it is along the Purcell front, and where cover on the floor is generally thin. In this region, outcrops of either Purcell or Rocky Mountain type rocks occur in the Trench floor, depending on the exact location of the Purcell front. Both types have densities averaging close to 2.73 gms. per cc. The profiles at Marysville and Elko are in the area where the Trench lies completely within the Purcell mountains, where it is considerably broader than in the first two cases, and where cover on the Trench floor may be of considerable thickness. The Radium profile exhibits a decrease toward the west, where the contact of a granitic batholith is approached, and a narrow negative over the section

BOUGUER GRA

OF A PORTI

SOUTHERN BRITIS
AND ALB

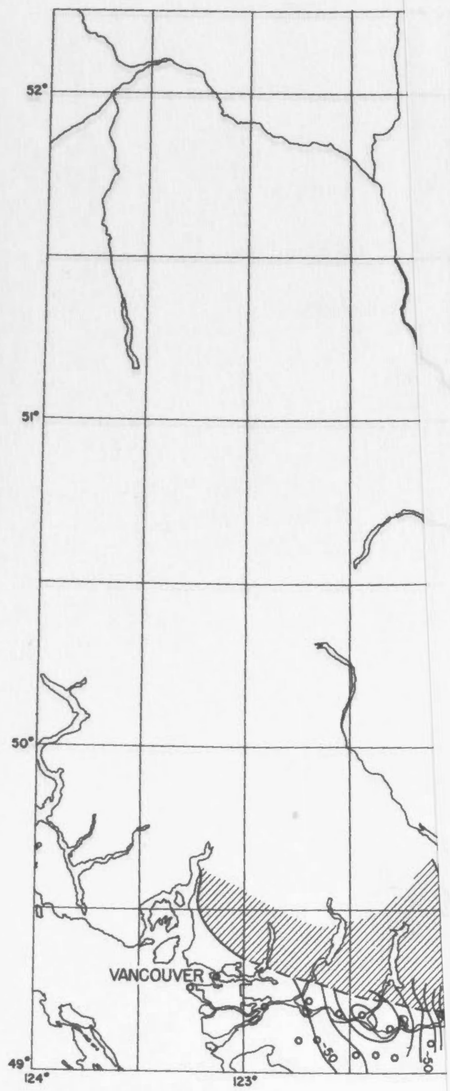
-150 CONTOUR INTERVAL

o GRAVITY STATION

AREAS OF COAST R
INTRUSIVE ROCKS (
AND TERTIARY).

SCALE

0 20



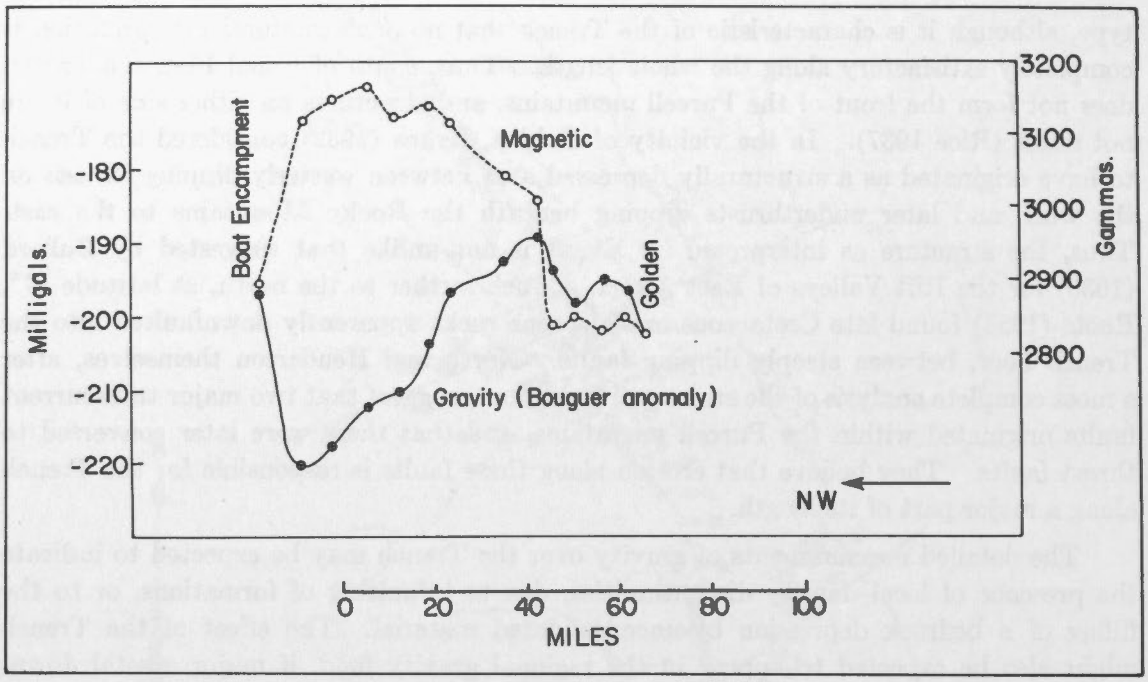


Figure 12. Gravity and magnetic profiles along the Rocky Mountain Trench between Golden and Boat Encampment. The latter station is at the northern extremity of the Big Bend of the Columbia River.

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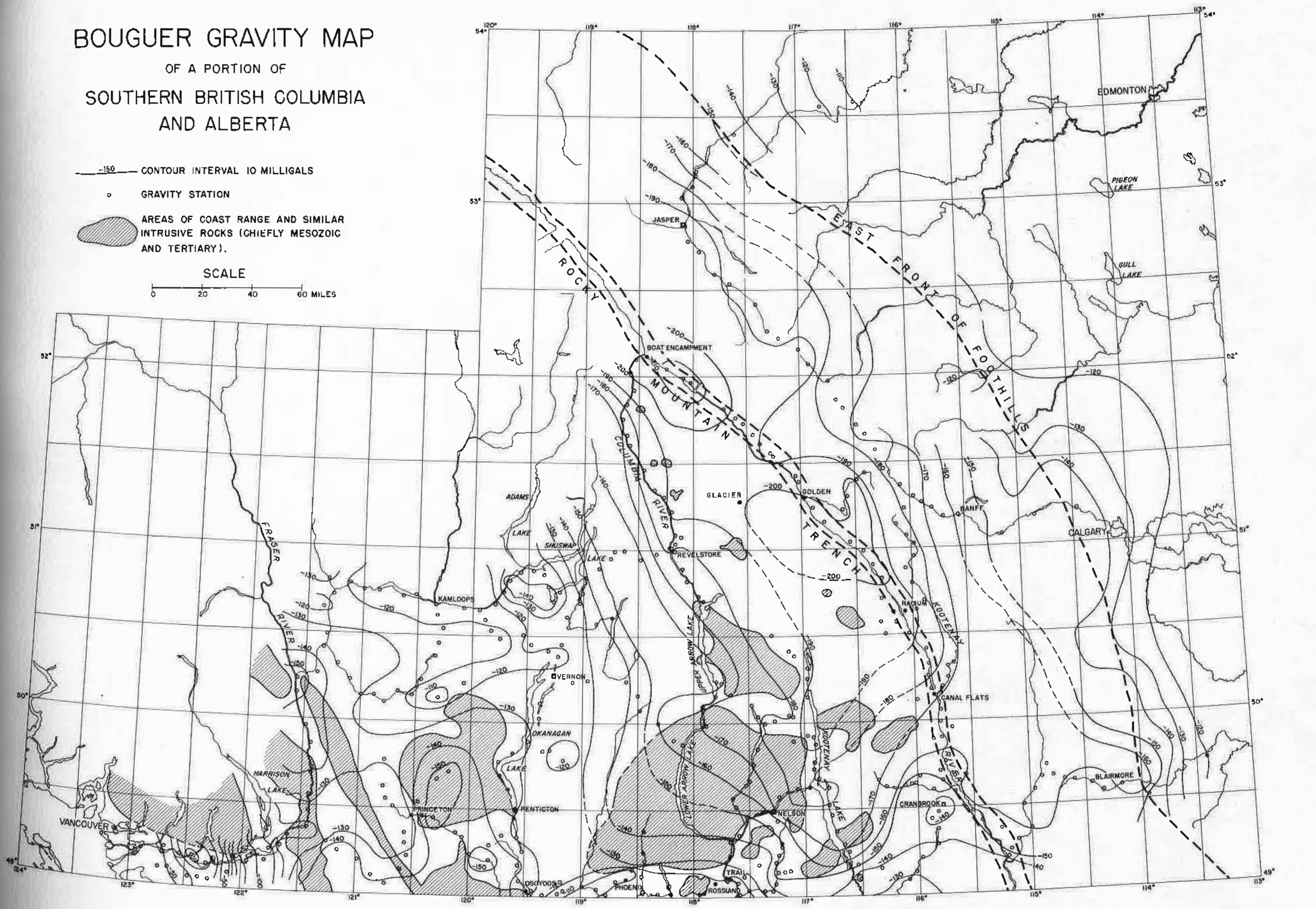
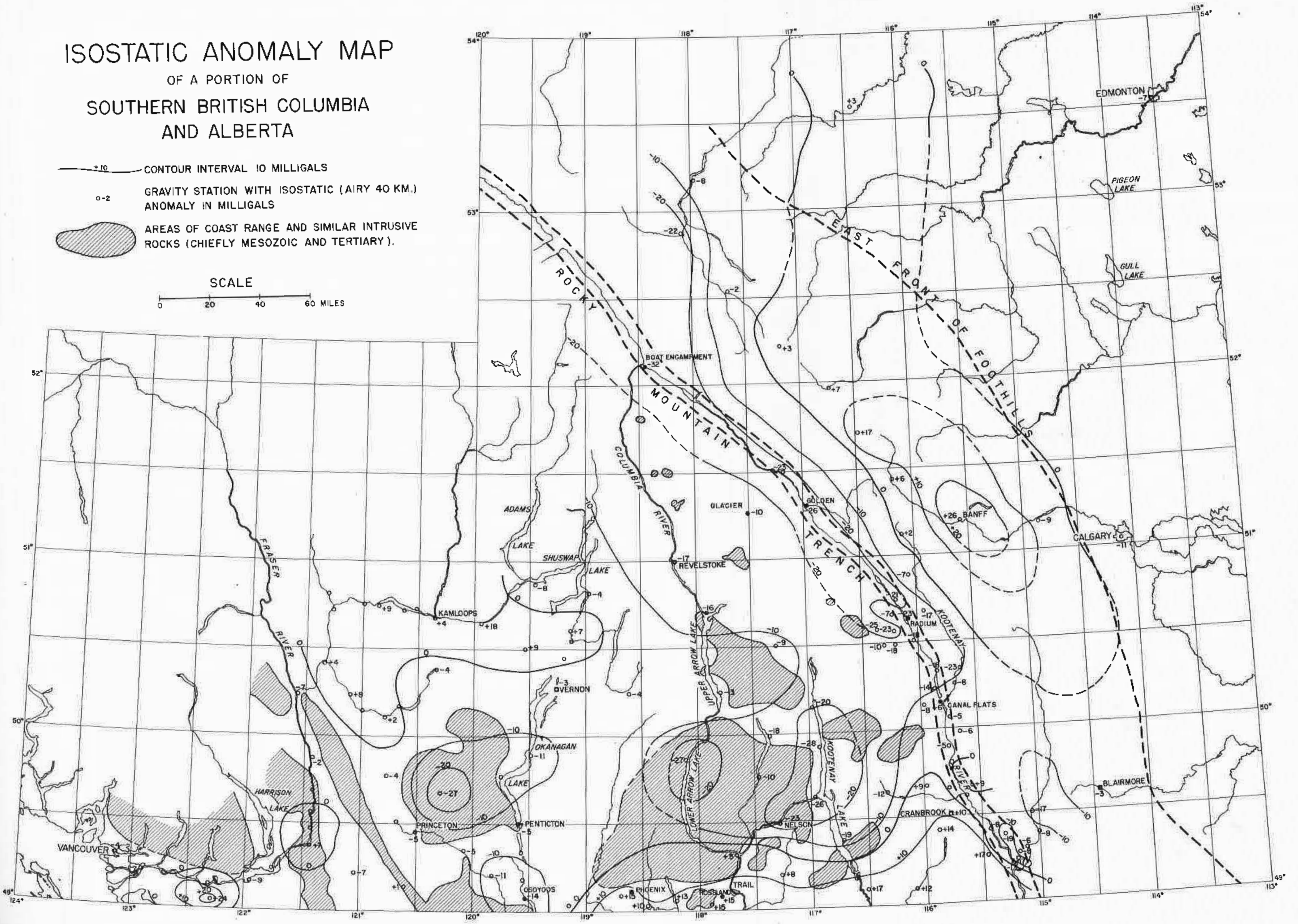


BOUGUER GRAVITY MAP
OF A PORTION OF
SOUTHERN BRITISH COLUMBIA
AND ALBERTA
-150 CONTOUR INTERVAL 10 MILLIGALS
GRAVITY STATION
AREAS OF COAST RANGE AND SIMILAR INTRUSIVE ROCKS (CHIEFLY MESOZOIC AND TERTIARY).
SCALE
0 20 40 60 MILES
EDMONTON
PIGEON LAKE
GULL LAKE
JASPER
EAST FRONT OF FOOTHILLS
ROCKY MOUNTAIN TRENCH
BOAT ENCAMPMENT
COLUMBIA RIVER
GLACIER
GOLDEN
BANFF
CALGARY
ADAMS LAKE
SHUSWAP LAKE
REVELSTOKE
FRASER RIVER
KAMLOOPS
RADIUM
KOOTENAY
VERNON
UPPER ARROW LAKE
CANAL FLATS
OKANAGAN LAKE
LOWER ARROW LAKE
KOOTENAY LAKE
KOOTENAY RIVER
HARRISON LAKE
BLAIRMORE
CRANBROOK
PRINCETON
PENTICTON
NELSON
VANCOUVER
OSOYOOS
PHOENIX
TRAIL
ROSSLAND


ISOSTATIC ANOMALY MAP
OF A PORTION OF
SOUTHERN BRITISH COLUMBIA
AND ALBERTA
+10 CONTOUR INTERVAL 10 MILLIGALS
o-2 GRAVITY STATION WITH ISOSTATIC (AIRY 40 KM.) ANOMALY IN MILLIGALS
AREAS OF COAST RANGE AND SIMILAR INTRUSIVE ROCKS (CHIEFLY MESOZOIC AND TERTIARY).
SCALE
0 20 40 60 MILES
EDMONTON
PIGEON LAKE
GULL LAKE
EAST FRONT OF FOOTHILLS
ROCKY MOUNTAIN TRENCH
BOAT ENCAMPMENT
COLUMBIA RIVER
GLACIER
GOLDEN
BANFF
CALGARY
REVELSTOKE
RADIUM
KOOTENAY
ADAMS LAKE
SHUSWAP LAKE
FRASER RIVER
KAMLOOPS
VERNON
UPPER ARROW LAKE
LOWER ARROW LAKE
KOOTENAY LAKE
CANAL FLATS
KOOTENAY RIVER
BLAIRMORE
CRANBROOK
OKANAGAN LAKE
HARRISON LAKE
PRINCETON
PENTICTON
NELSON
VANCOUVER
OSOYOOS
PHOENIX
ROSSLAND
TRAIL

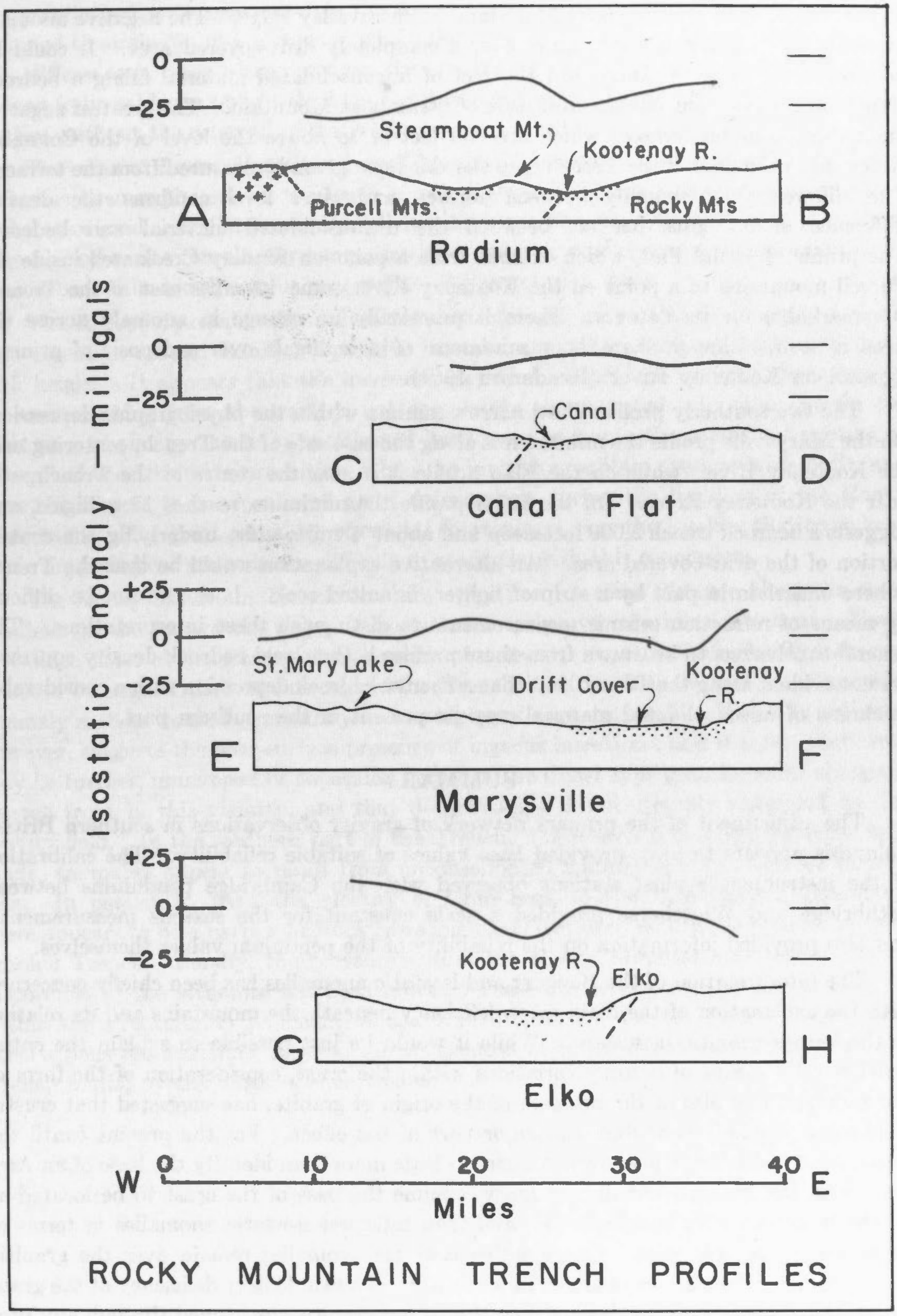


FIGURE 13. Isostatic anomaly profiles across the Rocky Mountain Trench. The locations of the profiles are shown in Figure 10.

of the Trench east of Steamboat Mountain, an intravalley ridge. The negative anomaly amounts to 16 milligals, and occurs over a completely drift-covered area. It could be accounted for by a thickness of 1,800 feet of unconsolidated material filling a bedrock trench on the east, but not the west, side of Steamboat Mountain. The greatest negative anomalies occur on terraces which are 300 feet or so above the level of the Columbia River cut in the floor of the Trench, and the thickness given is measured from the terraces. The difference in anomaly between terrace and river level confirms the density difference of 0.7 gms. per cc. between the unconsolidated material and bedrock. The profile at Canal Flat, which extends from a point on Findlay Creek well inside the Purcell mountains to a point on the Kootenay River some 10 miles east of the Trench, is remarkable for its flatness. There is practically no change in anomaly across the Trench itself, although there is a minimum of 4 milligals over a deposit of primary gypsum on Kootenay River (Henderson 1954).

The two southerly profiles show narrow minima within the physiographic depression. On the Marysville profile the minimum is along the east side of the Trench, centering near the Kootenay River, while on the Elko profile it is near the centre of the Trench, still near the Kootenay River. On the latter profile the minimum reaches 17 milligals, and suggests a bedrock trench 2,000 feet deep and about 4 miles wide, underlying the central portion of the drift-covered area. An alternative explanation would be that the Trench is here underlain in part by a strip of lighter, infaulted rock. It should not be difficult by means of refraction seismic measurements to distinguish these interpretations. The general conclusions to be drawn from these profiles is that local bedrock density contrasts are not evident along the Trench, but that a narrow bedrock depression with a considerable thickness of unconsolidated material may be present in the southern part.

SUMMARY

The adjustment of the primary network of gravity observations in southern British Columbia appears to have provided base values of suitable reliability. The calibration of the instrument against stations observed with the Cambridge pendulums between Lethbridge and Whitehorse provided a scale constant for the seasons measurements, and also provided information on the reliability of the pendulum values themselves.

The interpretation of the Bouguer and isostatic anomalies has been chiefly concerned with the explanation of the main mass deficiency beneath the mountains and its relation to the known granitic intrusions. While it would be just possible to explain the entire deficiency by means of density variations within the crust, consideration of the form of the anomaly, and also of the problem of the origin of granite, has suggested that crustal thickening probably contributes a major part of the effect. For the present (until the actual form of the crust is known) we can do little more than identify the base of an Airy crust with the Mohorovičić discontinuity, assume the base of the crust to be located at depths in accord with compensation, and then interpret isostatic anomalies in terms of departures from this state. Considerable isostatic anomalies remain over the granitic batholiths, but these are explainable in terms of the known density deficiency of the granitic rocks. However, it has been shown that if the granite was formed through any process of settling of denser constituents, there must be additional crustal thickening beneath the granite bodies to accommodate the denser fraction. Otherwise, the granite must be assumed to originate by a process in which the denser constituents are removed laterally. The difference in composition between the granitic rocks and the older formations would appear to be evidence against the hypothesis that the lower density arises from recrystallization without the removal of material.

The area of Lower Purcell sedimentation is characterized by a positive anomaly. This has been explained on the basis of relatively dense basic extrusive and intrusive rocks associated with the Lower Purcell formations. The important point is that there does not appear to remain any suggestion of a major crustal downwarp that might have been expected under this great geosyncline of Precambrian time.

The Rocky Mountains themselves are characterized, at least in the area of considerable elevation around Banff, by positive isostatic anomalies, showing some correlation with height. It appears that the increased elevation, which was brought about largely by overthrusting from the west, is not completely compensated. In other words, the crust as a whole appears to have adjusted itself more or less to the conditions existing at the end of the Laramide revolution, when the interior mountain systems were built, and does not appear to have suffered great deformation during the building of the Rocky Mountains. The great estimates of crustal shortening across the Rockies that have been made on geological grounds are difficult to reconcile with this conclusion.

The Rocky Mountain Trench occupies a position for some distance along the steep gradient on the east of the negative isostatic anomaly over the interior ranges. North of Golden most of the gravity stations were of necessity located within the Trench, and it could be argued that in this region the Trench itself is characterized by a negative anomaly such as would be caused by downwedging of a crustal block. Magnetic evidence, however, suggests the near-surface presence of ingeous intrusions, and it is felt that there may be further, unmapped or concealed bodies of the Coast type granitic rocks along the Purcell front in this vicinity, and that downwedging is not strongly suggested by the gravity field. In the southern part of the Trench, where several detailed traverses were made, anomalies appear to result from unconsolidated material filling a bedrock depression. In particular, from the vicinity of Cranbrook to the International Boundary, there appears to be a narrow bedrock rift some 2,000 feet deep within the broader physiographic Trench. Finally, the presence within the Rocky Mountains of certain trends discordant to the structure has been noted. These are believed to be due to features within the Precambrian basement, and a fruitful problem for the future, when more observations are available, may be the verification of transcurrent movement along the Trench faults, by the offset of such trends.

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APPENDIX

PRINCIPAL FACTS FOR GRAVITY STATIONS

No.	Station	Longitude	Latitude	Elevation	Observed Gravity	Free Air Anomaly	Bouguer Anomaly	Terrain	Curvature	T + C (A to 1)	Isostatic
		° ′	° ′	feet							(Airy—40 km.)
1	Lethbridge.................	112 50.0	49 42.3	2,977	980.7604	−0.0122	−0.1136				
2	Macleod....................	113 24.9	49 43.8	3,116	.7547	− .0069	− .1130				
3	Pincher....................	113 57.0	49 31.0	3,771	.6623	− .0186	− .1470				
4	Blairmore..................	114 25.5	49 36.1	4,235	.6366	− .0084	− .1526	.0031	−.0014	.1479	−.0030
5	Natal......................	114 51.1	49 42.9	3,782	.6605	− .0372	− .1660				
6	Sentinel...................	114 34.4	49 37.5	4,444	.6203	− .0071	− .1585				
7	Crow's Nest................	114 41.1	49 37.7	4,451	.6249	− .0022	− .1537				
8	....	114 45.8	49 39.5	4,039	.6440	− .0245	− .1621				
9	Fernie.....................	115 03.3	49 30.2	3,310	.6726	− .0505	− .1632	.0034	−.0012	.1439	−.0171
10	Olson......................	114 54.2	49 39.1	3,535	.6693	− .0460	− .1664				
11	Howser.....................	114 57.5	49 35.2	3,453	.6682	− .0489	− .1665				
12	Elko.......................	115 06.5	49 18.1	3,088	.6774	− .0486	− .1537	.0026	−.0011	.1459	−.0064
13	Wardner....................	115 25.7	49 25.4	2,489	.7244	− .0688	− .1536	.0018	−.0010	.1451	−.0077
14	Cranbrook..................	115 45.6	49 31.1	3,011	.7158	− .0368	− .1393	.0010	−.0011	.1490	−.0096
15	Moyie......................	115 50.1	49 17.4	3,052	.6959	− .0324	− .1364				
16	Peavine Creek..............	115 49.4	49 22.1	3,051	.6986	− .0368	− .1407				
17	Yahk.......................	116 05.7	49 05.0	2,823	.7005	− .0309	− .1270	.0051	−.0011	.1351	.0121
18	Tochty.....................	115 59.3	49 12.2	2,970	.6904	− .0378	− .1390				
19	Ryan.......................	116 01.1	49 08.8	2,904	.6969	− .0325	− .1315				
20	Creston....................	116 31.0	49 06.0	1,987	.7429	− .0686	− .1363	.0032	−.0008	.1355	.0016
21	McConnell..................	116 20.1	49 09.4	2,441	.7182	− .0557	− .1388				
22	Sanca......................	116 43.6	49 22.6	1,819	.7358	− .1162	− .1782	.0132	−.0008	.1466	0.0192
23	Wynndel....................	116 33.1	49 10.7	1,850	.7480	− .0889	− .1519				
24	Sirdar.....................	116 37.2	49 14.9	1,807	.7335	− .1022	− .1638				
25	Kuskanook..................	116 39.5	49 17.9	1,773	.7306	− .1188	− .1792				
26	Kootenay Bay...............	116 52.3	49 40.5	1,763	.7683	− .1157	− .1757				
27	Boswell....................	116 45.8	49 27.6	1,770	.7470	− .1171	− .1774				
28	Lafrance Creek.............	116 46.9	49 31.5	1,780	.7543	− .1147	− .1753				
29	Gray Creek.................	116 47.3	49 37.4	1,781	.7516	− .1261	− .1867				
30	Balfour....................	116 57.5	49 37.5	1,763	.7547	− .1249	− .1849	.0115	−.0007	.1476	− .0265
31	Nelson.....................	117 17.6	49 29.6	1,823	.7537	− .1084	− .1705	.0103	−.0008	.1384	− .0226
32	....	117 15.5	49 29.1	2,885	.7019	− .0596	− .1579				
33	....	117 14.5	49 19.4	2,551	.7232	− .0552	− .1421				

34	Ymir	117	12.8	49	16.9	2,390	.7236	− .0663	− .1477				
35	Boulder Mill	117	14.3	49	14.4	2,272	.7379	− .0593	− .1367				
36	Salmo	117	16.8	49	11.8	2,176	.7388	− .0635	− .1376	.0087	− .0009	.1364	.0066
37	Sheep Creek Bridge	117	15.4	49	08.5	2,192	.7341	− .0619	− .1366				
38	....	117	11.4	49	08.4	2,650	.6928	− .0599	− .1502				
39	Sheep Creek	117	08.8	49	08.8	3,116	.6651	− .0444	− .1505				
40	....	117	16.3	49	04.7	2,061	.7412	− .0614	− .1316				
41	Nelway	117	18.3	49	00.1	2,559	.7108	− .0291	− .1253				
42	....	117	23.1	49	02.0	1,745	.7585	− .0698	− .1292				
43	....	117	30.4	49	02.2	1,891	.7656	− .0492	− .1136				
44	....	117	35.9	49	00.4	1,793	.7760	− .0453	− .1064				
45	....	117	37.1	49	05.0	1,352	.7921	− .0776	− .1237				
46	Fruitvale	117	32.5	49	06.9	1,979	.7646	− .0490	− .1165				
47	Parks	117	30.2	49	09.9	2,089	.7559	− .0519	− .1231				
48	Meadows	117	23.6	49	11.1	2,319	.7295	− .0584	− .1374				
49	Ainsworth	116	54.5	49	44.2	1,798	.7531	− .1331	− .1943				
50	Woodbury Creek	116	54.4	49	46.5	1,799	.7536	− .1360	− .1973				
51	Mirror Lake	116	54.0	49	52.6	1,772	.7667	− .1333	− .1947				
52	Kaslo	116	54.4	49	54.8	1,768	.7703	− .1345	− .1946	.0111	− .0007	.1564	− .0278
53	Lardeau	116	57.2	50	08.8	1,763	.7899	− .1361	− .1961	.0201	− .0007	.1566	− .0201
54	Marblehead	116	57.7	50	14.8	1,807	.8073	− .1234	− .1850				
55	Howser	116	58.8	50	18.5	1,859	.8126	− .1188	− .1822				
56	Goldhill	117	04.8	50	23.1	2,048	.8070	− .1134	− .1831				
57	Gerrard	117	17.3	50	30.8	2,350	.7933	− .1110	− .1900	.0196	− .0009	.1622	− .0091
58	....	117	07.9	50	25.0	2,160	.8031	− .1094	− .1831				
59	Shutty Creek	116	53.9	49	57.9	1,762	.7643	− .1457	− .2057				
60	Bear Creek	117	07.0	50	02.5	3,016	.7184	− .0803	− .1830				
61	Retallack	117	08.5	50	04.0	3,344	.7064	− .0637	− .1776				
62	Three Forks	117	17.4	50	01.9	2,591	.7436	− .0942	− .1824				
63	Denver Canyon	117	21.7	49	59.9	2,095	.7721	− .1095	− .1809	.0106	− .0008	.1527	− .0184
64	Roseberry	117	24.9	50	02.5	1,788	.7940	− .1202	− .1811				
65	Brouse	117	45.0	50	14.0	1,953	.8273	− .0885	− .1550				
66	Nakusp	117	48.0	50	14.3	1,478	.8536	− .1074	− .1577	.0061	− .0007	.1497	− .0026
67	....	117	47.9	50	09.2	1,415	.8361	− .1232	− .1714				
68	East Arrow Park	117	55.6	50	05.4	1,422	.8353	− .1176	− .1661				
69	Burton	117	53.8	49	59.5	1,406	.8206	− .1253	− .1731				
70	Summit Lake	117	39.0	50	09.1	2,494	.7726	− .0851	− .1701				
71	....	117	27.5	50	05.2	1,890	.8004	− .1082	− .1726				
72	....	116	58.7	49	55.8	2,276	.7447	− .1138	− .1912				
73	Cork Mine	117	04.4	49	54.5	3,405	.6735	− .0768	− .1928				
74	....	117	05.1	49	36.7	1,790	.7526	− .1232	− .1842				

PRINCIPAL FACTS FOR GRAVITY STATIONS—*Continued*

No.	Station	Longitude	Latitude	Elevation	Observed Gravity	Free Air Anomaly	Bouguer Anomaly	Terrain	Curvature	T + C (A to 1)	Isostatic
		° ′	° ′	feet							(Airy—40 km.)
75	....	117 13.8	49 34.3	1,766	980.7437	−0.1309	−0.1910				
76	Castlegar..................	117 39.9	49 19.5	1,435	.7989	− .0847	− .1336	.0075	− .0006	.1312	.0045
77	Taghum....................	117 23.6	49 29.8	1,757	.7681	− .1005	− .1604				
78	South Slocan..............	117 31.5	49 27.1	1,625	.7909	− .0861	− .1415				
79	Slocan Park................	117 36.9	49 31.1	1,600	.7901	− .0952	− .1497				
80	Vallican....................	117 38.9	49 33.5	1,641	.7871	− .0979	− .1538				
81	Winlaw......................	117 34.1	49 37.2	1,714	.7847	− .0990	− .1574				
82	Slocan.......................	117 28.1	49 48.1	1,764	.7850	− .1103	− .1704	.0142	− .0007	.1473	− .0096
83	Enterprise Landing..........	117 25.5	49 51.7	2,010	.7693	− .1080	− .1765				
84	Perry's......................	117 30.1	49 40.1	1,722	.7793	− .1079	− .1666				
85	Thrum's....................	117 34.9	49 21.3	1,506	.7871	− .0924	− .1437				
86	Rossland...................	117 47.8	49 04.7	3,385	.6839	.0058	− .1095				
87	Blueberry Creek............	117 39.7	49 14.8	1,568	.7844	− .0796	− .1330				
88	Hanna......................	117 44.7	49 07.7	1,479	.7845	− .0772	− .1278				
89	Rossland...................	117 47.9	49 04.8	3,465	.6786	.0081	− .1101	.0024	− .0012	.1240	.0151
90	Big Sheep Creek............	117 56.8	49 00.9	2,238	.7362	− .0441	− .1203				
91	Summit......................	117 53.9	49 01.8	4,594	.6037	.0437	− .1128	.0055	− .0014	.1236	.0149
92	Cascade....................	118 12.4	49 01.1	1,581	.7857	− .0567	− .1105				
93	Grand Forks...............	118 26.8	49 02.1	1,685	.7805	− .0536	− .0110	.0036	− .0007	.1179	.0098
94	Gilpin.......................	118 18.7	49 00.8	1,672	.7779	− .0554	− .1124				
95	Fife.........................	118 12.2	49 04.0	1,968	.7642	− .0461	− .1131	.0055	− .0009	.1224	.0129
96	Troutdale..................	118 28.0	49 06.9	1,763	.7743	− .0597	− .1197				
97	Stanwell....................	118 25.9	49 12.1	1,852	.7662	− .0671	− .1302				
98	Archibald..................	118 27.2	49 15.1	1,903	.7225	− .0705	− .1353				
99	Burrell Creek...............	118 27.2	49 22.2	2,094	.7564	− .0691	− .1405				
100	Greenwood.................	118 40.6	49 06.0	2,457	.7388	− .0284	− .1122	.0040	− .0009	.1235	.0144
101	Eholt.......................	118 32.3	49 09.5	3,087	.7106	− .0027	− .1079				
102	Jewel Lake.................	118 37.3	49 09.9	3,711	.6739	.0187	− .1077				
103	Phoenix.....................	118 36.3	49 05.8	4,529	.6286	.0565	− .0978				
104	Rock Creek.................	118 59.3	49 03.1	1,982	.7684	− .0393	− .1068				
105	Midway.....................	118 47.1	49 00.9	1,906	.7632	− .0483	− .1132				
106	Kettle River Crossing.......	118 52.5	49 02.6	1,936	.7682	− .0430	− .1089				
107	Osoyoos....................	119 27.5	49 01.8	952	.7970	− .1055	− .1380				

108	Bridesville	119	09.4	49	02.1	3,373	.6794	.0041	– .1108				
109	Summit (Anarchist)	119	11.9	49	00.9	4,049	.6398	.0298	– .1081				
110		119	20.0	49	00.5	3,714	.6523	.0114	– .1151				
111		119	25.8	49	01.6	1,004	.7942	– .1032	– .1374				
112	Okanagan Falls	119	34.5	49	20.8	1,119	.8258	– .0893	– .1275				
113		119	33.5	49	06.0	927	.8017	– .1095	– .1411	.0076	– .0004	.1198	– .0141
114	Oliver	119	33.2	49	11.5	971	.8091	– .1062	– .1393				
115		119	32.1	49	15.0	1,077	.8173	– .0932	– .1299				
116	Penticton	119	35.8	49	30.9	1,128	.8347	– .0947	– .1331	.0049	– .0006	.1239	– .0049
117	Skaha	119	36.4	49	27.0	1,115	.8279	– .0969	– .1349				
118		119	40.8	49	22.1	2,215	.7558	– .0583	– .1337				
119	Cedar Creek	119	49.4	49	17.9	1,782	.7663	– .0823	– .1462				
120	Keremeos	119	49.5	49	12.2	1,355	.7801	– .1000	– .1462	.0106	– .0006	.1254	– .0108
121	Hedley	120	04.4	49	20.9	1,716	.7726	– .0866	– .1450	.0138	– .0007	.1271	– .0048
122		119	55.2	49	13.2	1,430	.7624	– .1122	– .1609				
123		119	59.9	49	14.5	1,547	.7627	– .1029	– .1556				
124	Princeton	120	30.2	49	27.8	2,098	.7790	– .0547	– .1260	.0024	– .0008	.1238	– .0006
125		120	12.2	49	23.4	1,807	.7681	– .0862	– .1478				
126		120	18.7	49	26.6	1,895	.7634	– .0875	– .1520				
127		120	24.7	49	27.6	1,987	.7688	– .0749	– .1426				
128	Bonnevrier Creek	120	37.5	49	08.6	3,383	.6655	– .0186	– .1338	.0059	– .0012	.1297	.0008
129	Whipsaw Creek	120	34.1	49	21.9	2,686	.7493	– .0201	– .1116				
130		120	34.2	49	18.9	3,949	.6685	.0222	– .1123				
131	Sunday Summit	120	33.3	49	14.0	4,126	.6361	.0139	– .1266				
132	Skagit Creek	121	00.6	49	12.9	2,524	.7077	– .0636	– .1496	.0215	– .0010	.1223	– .0068
133		120	44.1	49	04.1	3,710	.6283	– .0183	– .1447				
134	Allison Pass	120	51.7	49	06.9	4,400	.6037	.0178	– .1321				
135	Hope (CNR)	121	25.9	49	22.2	157	.8929	– .1148	– .1202				
136	Nineteen Mile Creek	121	09.5	49	14.2	2,100	.7332	– .0799	– .1514				
137	11 Mile Creek	121	16.7	49	19.3	1,876	.7796	– .0622	– .1261				
138	Hope (CPR)	121	26.7	49	22.9	137	.9002	– .1105	– .1152	.0096	– .0002	.1126	.0068
139	Chilliwack	121	57.1	49	09.8	32	.9089	– .0922	– .0933	.0018	– .0000	.0821	– .0092
140	Laidlaw	121	36.9	49	19.9	90	.9024	– .1083	– .1114				
141	Cheam View	121	40.3	49	16.8	100	.8864	– .1187	– .1221				
142	Rosedale	121	48.3	49	10.7	47	.8929	– .1081	– .1097				
143	Aldergrove	122	28.5	49	03.5	336	.9393	– .0238	– .0352				
144		122	07.4	49	05.4	15	.9346	– .0615	– .0620	.0000	– .0002	.0594	.0240
145	Abbotsford	122	17.1	49	03.0	88	.9502	– .0354	– .0384				
146		122	22.9	49	03.5	304	.9444	– .0217	– .0321				
147	New Westminster	122	54.4	49	12.1	64	.9487	– .0528	– .0550				
148	Langley Prairie	122	39.2	49	06.2	38	.9458	– .0493	– .0506				

PRINCIPAL FACTS FOR GRAVITY STATIONS—*Continued*

No.	Station	Longitude	Latitude	Elevation	Observed Gravity	Free Air Anomaly	Bouguer Anomaly	Terrain	Curvature	T + C (A to 1)	Isostatic
		° ′	° ′	feet							(Airy—40 km.)
149	Cloverdale................	122 44.0	49 06.2	13	980.9447	−0.0528	−0.0532				
150	Vancouver, Brockton Point...	123 07.0	49 18.0	34	.9597	− .0534	− .0546	.0008	− .0000	.0496	−.0042
151	Coquitlam................	122 48.0	49 17.2	34	.9610	− .0509	− .0521				
152	Vancouver (UBC)..........	123 15.4	49 16.2	285	.9366	− .0502	− .0599				
153	Mission..................	122 18.5	49 08.0	27	.9763	− .0226	− .0235				
154	Pitt Meadows.............	122 41.3	49 13.6	23	.9534	− .0541	− .0549				
155	Albion...................	122 33.2	49 11.0	28	.9639	− .0393	− .0402				
156	Ruskin...................	122 25.7	49 10.4	33	.9837	− .0181	− .0192				
157	Agassiz..................	121 46.0	49 14.4	59	.8977	− .1076	− .1097				
158	Deroche..................	122 04.3	49 11.2	50	.9440	− .0574	− .0591				
159	Spuzzum..................	121 24.7	49 41.4	398	.8877	− .1260	− .1395				
160	Choate...................	121 25.7	49 28.4	212	.8961	− .1158	− .1230				
161	Yale.....................	121 25.9	49 33.8	221	.8934	− .1256	− .1331				
162	Boston Bar...............	121 26.7	49 51.9	453	.8960	− .1281	− .1435	.0177	− .0002	.1233	− .0025
163	Chapman's................	121 25.2	49 43.0	358	.8859	− .1339	− .1461				
164	Lytton...................	121 35.0	50 14.0	566	.9114	− .1349	− .1541	.0161	− .0002	.1313	− .0068
165	Boothroyd................	121 28.1	49 57.1	571	.8987	− .1221	− .1415				
166	Cisco....................	121 34.7	50 08.9	604	.8966	− .1386	− .1592				
167	Spence's Bridge..........	121 21.0	50 24.5	774	.9304	− .1119	− .1383	.0159	− .0003	.1262	.0035
168	....	121 23.6	50 16.5	677	.9211	− .1185	− .1416				
169	Drynock..................	121 23.5	50 20.5	755	.9195	− .1186	− .1443				
170	Cache Creek..............	121 19.5	50 48.3	1,498	.9301	− .0793	− .1303				
171	Martel...................	121 18.3	50 28.5	818	.9394	− .1048	− .1326				
172	....	121 20.9	50 39.0	1,530	.9257	− .0670	− .1191				
173	Ashcroft.................	121 16.5	50 43.6	993	.9635	− .0863	− .1201	.0065	− .0005	.1232	.0091
174	Savona...................	120 50.5	50 45.0	1,163	.9607	− .0752	− .1148				
175	McAbee...................	121 07.9	50 46.8	1,033	.9672	− .0836	− .1188				
176	Walhachin................	120 59.3	50 45.2	1,257	.9548	− .0726	− .1154				
177	Kamloops.................	120 20.0	50 40.6	1,150	.9529	− .0776	− .1168	.0030	− .0005	.1177	.0034
178	Cherry Creek.............	120 38.4	50 43.1	1,142	.9610	− .0741	− .1130				
179	Tranquille...............	120 31.0	50 43.3	1,184	.9571	− .0743	− .1147				
180	Kamloops (CPR)...........	120 19.0	50 40.2	1,161	.9507	− .0782	− .1177				
181	....	120 19.0	50 36.8	2,656	.8678	− .0157	− .1061				

182	....	120	15.5	50	32.7	2,321	.8658	− .0431	− .1221				
183	....	120	17.4	50	26.8	2,374	.8365	− .0587	− .1396				
184	....	120	27.3	50	14.4	2,053	.8503	− .0563	− .1262				
185	....	120	32.1	50	09.1	2,048	.8497	− .0500	− .1197				
186	Nicola....................	120	40.1	50	09.8	2,048	.8472	− .0525	− .1232				
187	Merritt....................	120	47.2	50	06.5	1,954	.8423	− .0623	− .1289	.0028	− .0008	.1288	.0019
188	Coyle......................	120	52.8	50	08.8	1,875	.8426	− .0728	− .1367				
189	Canford..................	121	00.0	50	08.2	1,727	.8618	− .0667	− .1255				
190	Dot.........................	121	06.0	50	13.8	1,463	.8787	− .0829	− .1326	.0101	− .0006	.1311	.0079
191	Clapperton...............	121	12.8	50	19.8	1,139	.9062	− .0949	− .1337				
192	Chapperon Lake...........	120	03.5	50	13.3	3,051	.7965	− .0150	− .1189				
193	Douglas Lake.............	120	17.1	50	08.4	2,633	.8239	− .0196	− .1093				
194	Thallia....................	120	45.6	49	46.4	2,859	.7550	− .0347	− .1321	.0037	− .0011	.1251	− .0044
195	Manning..................	120	47.1	49	38.7	2,630	.7615	− .0383	− .1279				
196	Tulameen.................	120	45.5	49	32.6	2,557	.7680	− .0295	− .1166				
197	Coalmont.................	120	41.6	49	30.7	2,442	.7709	− .0346	− .1178				
198	Osprey Lake..............	120	11.1	49	43.1	3,601	.6813	− .0337	− .1563				
199	Jellicoe...................	120	16.9	49	40.4	3,357	.6922	− .0417	− .1560	.0045	− .0012	.1255	− .0272
200	Jura........................	120	27.0	49	32.6	3,041	.7222	− .0298	− .1333				
201	Stump Lake..............	120	19.8	50	22.8	2,473	.8367	− .0432	− .1274	.0020	− .0010	.1220	− .0044
202	Monte Creek..............	119	57.1	50	38.9	1,154	.9622	− .0657	− .1051	.0053	− .0005	.1177	.0174
203	Campbell Creek............	120	04.8	50	39.6	1,151	.9484	− .0808	− .1200				
204	Sorrento..................	119	28.1	50	52.5	1,366	.9449	− .0830	− .1295	.0031	− .0006	.1189	− .0081
205	Pritchard.................	119	48.9	50	41.1	1,151	.9613	− .0699	− .1091				
206	B.M. 344C................	119	45.0	50	45.4	1,140	.9336	− .1051	− .1439				
207	Chase.....................	119	41.7	50	49.0	1,184	.9316	− .1083	− .1487				
208	Squilax....................	119	35.4	50	51.7	1,299	.9388	− .0942	− .1385				
209	Salmon Arm...............	119	16.8	50	42.1	1,159	.9307	− .1013	− .1408				
210	....	119	22.5	50	51.1	1,498	.9350	− .0784	− .1294				
211	Tappen....................	119	20.0	50	46.9	1,159	.9333	− .1059	− .1448				
212	Grindrod..................	119	08.8	50	36.8	1,210	.9396	− .0799	− .1211	.0031	− .0006	.1255	.0069
213	Canoe......................	119	13.4	50	45.1	1,150	.9435	− .0938	− .1330				
214	....	119	12.4	50	39.9	1,700	.9091	− .0690	− .1269				
215	Vernon.....................	119	16.1	50	15.9	1,251	.9043	− .0804	− .1230	.0024	− .0006	.1177	− .0035
216	Sweetsbridge..............	119	28.8	50	27.1	1,748	.8919	− .0627	− .1222				
217	Falkland...................	119	33.2	50	30.0	1,921	.8913	− .0511	− .1165	.0080	− .0008	.1185	.0092
218	Westwold.................	119	45.0	50	28.7	2,070	.8668	− .0599	− .1304				
219	Monte Lake...............	119	50.7	50	31.5	2,280	.8696	− .0413	− .1190				
220	Ducks Meadow............	119	53.9	50	34.7	2,141	.8892	− .0396	− .1124				
221	O'Keefe....................	119	19.1	50	24.2	1,553	.9007	− .0678	− .1207				
222	Lumby......................	118	57.5	50	15.0	1,624	.8771	− .0711	− .1265				

PRINCIPAL FACTS FOR GRAVITY STATIONS—*Continued*

No.	Station	Longitude	Latitude	Elevation	Observed Gravity	Free Air Anomaly	Bouguer Anomaly	Terrain	Curvature	T + C (A to 1)	Isostatic
		° ′	° ′	feet							(Airy—40 km.)
223	Pass Creek.................	118 30.5	50 09.8	2,880	980.7777	−0.0447	−0.1428				
224	Kettle River...............	118 28.9	50 04.8	3,854	.7067	− .0166	− .1479				
225	Inonaklin River............	118 20.5	50 00.0	3,557	.7050	− .0390	− .1602				
226	Needles....................	118 05.5	49 52.0	1,423	.8204	− .1125	− .1610	.0059	− .0006	.1283	− .0274
227	....	118 11.2	49 55.2	1,606	.8098	− .1107	− .1654				
228	Cherryville................	118 36.0	50 14.6	1,780	.8585	− .0745	− .1351	.0043	− .0007	.1274	− .0041
229	Lavington..................	119 06.0	50 14.1	1,719	.8703	− .0677	− .1263				
230	Vernon.....................	119 16.1	50 15.9	1,244	.9050	− .0804	− .1228				
231	Kelowna....................	119 29.1	49 53.8	1,131	.8686	− .0839	− .1330	.0025	− .0004	.1200	− .0109
232	Oyama......................	119 22.5	50 06.7	1,291	.8863	− .0810	− .1249				
233	Winfield...................	119 23.9	50 01.3	1,400	.8691	− .0798	− .1275				
234	Rutland....................	119 24.0	49 55.0	1,330	.8645	− .0817	− .1270				
235	Peachland..................	119 44.5	49 46.7	1,129	.8529	− .1000	− .1385				
236	Westbank...................	119 37.2	49 50.1	1,129	.8623	− .0955	− .1340				
237	Greata.....................	119 44.7	49 42.3	1,130	.8469	− .0993	− .1378				
238	Summerland.................	119 39.5	49 36.5	1,129	.8421	− .0956	− .1341				
239	Klo Creek..................	119 21.8	49 49.3	1,847	.8314	− .0579	− .1208				
240	....	119 16.4	49 50.1	2,934	.7705	− .0175	− .1174				
241	McCulloch..................	119 10.9	49 46.9	4,130	.6938	.0229	− .1178				
242	Larkin.....................	119 14.1	50 22.3	1,306	.9158	− .0732	− .1176				
243	Armstrong..................	119 11.3	50 27.0	1,177	.9256	− .0823	− .1226				
244	Enderby....................	119 08.0	50 33.3	1,160	.9347	− .0841	− .1238				
245	....	118 53.4	50 34.1	1,230	.9215	− .0919	− .1340				
246	Mable Lake.................	118 44.0	50 36.1	1,307	.9109	− .0983	− .1430				
247	Sicamous...................	118 59.5	50 50.3	1,155	.9464	− .0979	− .1374	.0066	− .0006	.1273	− .0041
248	....	119 03.1	50 40.9	1,177	.9388	− .0895	− .1298				
249	....	119 01.5	50 45.1	1,151	.9470	− .0900	− .1294				
250	Taft.......................	118 35.9	50 59.5	1,281	.9283	− .1178	− .1616				
251	Cambie.....................	118 52.2	50 53.5	1,175	.9383	− .1091	− .1491				
252	....	118 46.1	50 56.7	1,212	.9347	− .1140	− .1553				
253	Craigellachie..............	118 43.2	50 58.5	1,226	.9390	− .1111	− .1528				
254	Revelstoke.................	118 12.0	51 00.0	1,496	.9050	− .1216	− .1725	.0087	− .0007	.1477	− .0168
255	....	118 29.0	50 56.5	1,666	.9037	− .1019	− .1586				

256	....	118	21.5	50	58.1	1,842	.8718	− .1197	− .1825				
257	Greenslide................	118	06.1	50	53.0	1,485	.8853	− .1319	− .1827				
258	....	118	04.0	50	49.1	1,422	.8906	− .1271	− .1756				
259	Sidmouth.................	117	57.5	50	44.1	1,410	.8849	− .1265	− .1745				
260	Arrowhead................	117	54.8	50	42.3	1,407	.8781	− .1309	− .1788	.0188	− .0006	.1442	− .0164
261	Revelstoke................	118	11.1	50	59.9	1,496	.9067	− .1201	− .1710				
262	....	118	11.0	51	01.0	3,929	.7609	− .0383	− .1722				
263	Mt. Revelstoke............	118	08.4	51	03.1	6,230	.6103	.0243	− .1879				
264	Carnes Creek.............	118	22.3	51	17.6	1,705	.9053	− .1278	− .1859				
265	Silvertip Falls.............	118	09.9	51	04.9	1,623	.8904	.1316	− .1869				
266	Laforme Creek............	118	11.9	51	13.0	1,813	.8859	− .1311	− .1919				
267	Downie Creek.............	118	27.8	51	27.5	1,628	.9281	− .1269	− .1823				
268	Mars Creek................	118	22.6	51	20.6	1,641	.9129	− .1344	− .1863				
269	Goldstream...............	118	36.8	51	39.0	1,806	.9491	− .1059	− .1674				
270	....	118	35.0	51	35.3	1,910	.9208	− .1189	− .1876				
271	Birch Creek...............	118	33.3	51	55.3	1,910	.9438	− .1253	− .1904				
272	Nickel Creek..............	118	38.5	51	44.8	2,002	.9414	− .1036	− .1718				
273	Bigmouth Creek...........	118	36.1	51	50.1	1,860	.9528	− .1132	− .1766				
274	Boat Encampment..........	118	26.1	52	06.9	1,950	.9518	− .1306	− .1970	.0065	− .0008	.1593	− .0320
275	Mica Creek................	118	33.7	52	00.8	1,862	.9487	− .1328	− .1962				
276	Potlach Creek.............	118	32.0	52	06.1	1,932	.9476	− .1353	− .2011				
277	Kinbasket.................	118	01.7	51	57.6	2,214	.9070	− .1369	− .2124				
278	Cummins Creek...........	118	13.2	52	02.3	2,187	.9071	− .1461	− .2206				
279	Tsar Creek................	118	04.5	51	59.1	2,252	.9019	− .1409	− .2176				
280	Bush River................	117	36.2	51	45.7	2,378	.8952	− .1158	− .1968				
281	Boulder Creek.............	117	52.8	51	52.5	2,265	.8983	− .1332	− .2104				
282	Big Foster Creek...........	117	42.1	51	48.1	2,335	.8936	− .1242	− .2037				
283	Bluewater Creek...........	117	14.1	51	32.0	2,625	.8630	− .1045	− .1939				
284	....	117	26.5	51	39.2	3,232	.8388	− .0824	− .1925				
285	....	117	18.0	51	33.2	3,065	.8430	− .0719	− .1893				
286	Golden....................	116	57.9	51	17.9	2,580	.8351	− .1162	− .2041	.0069	− .0010	.1725	− .0257
287	Donald....................	117	09.9	51	29.2	2,581	.8573	− .1105	− .1984	.0069	− .0010	.1703	− .0232
288	Blaeberry River...........	117	03.3	51	25.7	2,571	.8560	− .1076	− .1951				
289	Moberly...................	117	01.1	51	23.0	2,554	.8519	− .1092	− .1962				
290	Parson....................	116	35.5	51	04.2	2,587	.8087	− .1216	− .2097				
291	Nicholson.................	116	54.2	51	14.5	2,581	.8295	− .1166	− .2045				
292	McMurdo..................	116	46.1	51	08.5	2,583	.8152	− .1219	− .2100				
293	Brisco.....................	116	16.9	50	49.9	2,601	.7870	− .1209	− .2095				
294	Harrogate.................	116	27.5	50	59.0	2,591	.8000	− .1224	− .2006				
295	Spillimacheen.............	116	22.0	50	54.5	2,601	.7917	− .1230	− .2116				
296	Invermere.................	116	01.2	50	30.2	2,710	.7679	− .1006	− .1929	.0042	− .0010	.1712	− .0185

PRINCIPAL FACTS FOR GRAVITY STATIONS—*Continued*

No.	Station	Longitude	Latitude	Elevation	Observed Gravity	Free Air Anomaly	Bouguer Anomaly	Terrain	Curvature	T + C (A to 1)	Isostatic
		° ′	° ′	feet							(Airy—40 km.)
297	Radium Junction...........	116 04.2	50 37.2	2,875	980.7645	−0.0990	−0.1969	.0059	− .0011	.1687	− .0234
298	Kindersley Creek..........	116 10.3	50 44.2	2,689	.7816	− .1096	− .2012	.0065	− .0010	.1751	− .0206
299	....	116 08.1	50 42.8	2,881	.7695	− .1015	− .1996	.0059	− .0011	.1735	− .0213
300	....	116 06.9	50 41.1	2,687	.7788	− .1080	− .1995	.0069	− .0010	.1731	− .0205
301	....	116 04.9	50 39.2	2,904	.7651	− .0986	− .1974				
302	Radium Station...........	116 05.6	50 37.5	2,621	.7839	− .1040	− .1933	.0057	− .0010	.1709	− .0177
303	....	116 03.0	50 36.0	3,199	.7442	− .0870	− .1960	.0042	− .0012	.1720	− .0210
304	....	116 01.8	50 34.1	2,887	.7605	− .0972	− .1956	.0053	− .0010	.1722	−0.0191
305	....	116 00.3	50 32.0	2,918	.7539	− .0977	− .1971	.0027	− .0011	.1692	− .0263
306	....	115 59.9	50 30.9	2,855	.7561	− .0999	− .1971	.0042	− .0011	.1728	− .0212
307	....	116 22.9	50 33.8	3,599	.6979	− .0924	− .2150	.0212	− .0013	.1673	− .0278
308	....	116 19.7	50 34.3	3,553	.7094	− .0860	− .2070	.0153	− .0013	.1678	− .0252
309	....	116 17.6	50 34.2	3,526	.7140	− .0837	− .2038	.0132	− .0013	.1673	− .0246
310	....	116 15.6	50 33.9	3,537	.7188	− .0775	− .1980	.0106	− .0013	.1659	− .0228
311	....	116 14.0	50 33.7	3,480	.7242	− .0772	− .1957	.0077	− .0013	.1631	− .0262
312	....	116 12.2	50 33.5	3,469	.7265	− .0756	− .1938	.0060	− .0012	.1651	− .0239
313	....	116 09.8	50 33.0	3,464	.7315	− .0703	− .1883	.0032	− .0012	.1655	− .0202
314	....	116 06.8	50 32.4	3,126	.7514	− .0813	− .1877	.0031	− .0012	.1702	− .0156
315	....	116 05.4	50 32.8	2,934	.7634	− .0879	− .1879	.0032	− .0011	.1703	− .0155
316	Wilmer....................	116 03.4	50 32.0	2,863	.7677	− .0891	− .1866	.0037	− .0011	.1702	− .0138
317	....	116 04.6	50 34.0	2,850	.7692	− .0918	− .1889	.0034	− .0011	.1720	− .0146
318	....	116 06.0	50 35.0	2,827	.7707	− .0940	− .1903	.0034	− .0011	.1705	− .0171
319	....	116 07.0	50 35.4	3,006	.7635	− .0850	− .1873	.0031	− .0011	.1718	− .0135
320	....	116 08.9	50 36.3	3,265	.7523	− .0732	− .1844	.0028	− .0012	.1725	− .0103
321	....	116 10.4	50 37.2	3,225	.7553	− .0753	− .1851	.0035	− .0012	.1725	− .0103
322	....	116 13.4	50 39.5	3,280	.7539	− .0750	− .1867	.0061	− .0012	.1743	− .0075
323	....	116 16.1	50 41.5	3,389	.7489	− .0724	− .1879	.0069	− .0012	.1743	− .0079
324	....	116 09.5	50 38.1	3,840	.7205	− .0527	− .1844	.0027	− .0014	.1722	− .0109
325	....	116 10.0	50 39.8	4,425	.6862	− .0354	− .1861				
326	Paradise Mine............	116 19.8	50 28.3	7,470	.4751	− .0569	− .1975	.0137	− .0017	.1732	− .0123
327	....	116 12.6	50 28.5	3,615	.6959	− .0852	− .2083	.0195	− .0012	.1716	− .0184
328	....	116 07.9	50 30.0	3,438	.7259	− .0738	− .1909	.0056	− .0012	.1716	− .0149
329	....	116 05.2	50 30.6	3,094	.7506	− .0824	− .1878	.0033	− .0011	.1707	− .0149

330	....	116	02.6	50	31.2	2,644	.7775	− .0987	− .1888	.0044	− .0010	.1690	− .0164
331	Canal Flats................	115	50.1	50	09.1	2,666	.7601	− .0814	− .1722	.0039	− .0010	.1628	− .0065
332	....	115	59.0	50	28.5	2,770	.7618	− .0988	− .1931	.0039	− .0010	.1685	− .0217
333	....	115	55.3	50	26.2	2,868	.7566	− .0912	− .1889	.0045	− .0011	.1681	− .0174
334	....	115	52.9	50	24.5	3,132	.7423	− .0782	− .1849	.0058	− .0012	.1683	− .0120
335	....	115	52.2	50	22.5	2,840	.7565	− .0885	− .1852	.0050	− .0011	.1683	− .0130
336	....	115	51.8	50	19.4	2,653	.7601	− .0980	− .1883	.0053	− .0010	.1663	− .0178
337	....	115	53.2	50	17.3	2,818	.7519	− .0875	− .1835	.0039	− .0011	.1642	− .0165
338	....	115	52.4	50	14.4	2,829	.7497	− .0843	− .1807	.0042	− .0011	.1631	− .0145
339	....	115	51.5	50	10.8	2,800	.7529	− .0784	− .1738	.0031	− .0011	.1640	− .0078
340	....	116	00.6	50	07.6	3,522	.6998	− .0589	− .1789	.0042	− .0012	.1676	− .0083
341	....	115	58.6	50	08.0	3,530	.7012	− .0574	− .1776	.0039	− .0012	.1665	− .0084
342	....	115	55.9	50	08.6	3,305	.7136	− .0670	− .1795	.0082	− .0012	.1651	− .0075
343	....	115	53.4	50	08.5	3,270	.7224	− .0614	− .1728	.0050	− .0012	.1652	− .0038
344	....	115	51.4	50	08.7	3,210	.7303	− .0595	− .1688	.0031	− .0012	.1639	− .0030
345	....	115	39.1	50	19.8	3,077	.7333	− .0855	− .1903	.0084	− .0011	.1603	− .0227
346	....	115	41.5	50	18.7	3,019	.7392	− .0834	− .1863	.0099	− .0011	.1648	− .0127
347	....	115	41.6	50	15.9	2,852	.7508	− .0833	− .1805	.0104	− .0011	.1641	− .0071
348	....	115	41.7	50	14.4	2,793	.7490	− .0884	− .1835	.0123	− .0011	.1639	− .0084
349	....	115	42.4	50	12.8	2,810	.7521	− .0813	− .1770	.0083	− .0011	.1636	− .0062
350	....	115	43.8	50	11.6	2,748	.7543	− .0831	− .1767	.0062	− .0010	.1612	− .0103
351	....	115	46.1	50	10.3	3,045	.7392	− .0684	− .1721	.0049	− .0011	.1625	− .0058
352	Canal Flats Village..........	115	48.2	50	09.2	2,679	.7599	− .0775	− .1688	.0025	− .0010	.1615	− .0058
353	Skookumchuck.............	115	44.1	49	54.7	2,563	.7512	− .0786	− .1659	.0026	− .0010	.1588	− .0055
354	....	115	46.4	50	07.2	2,737	.7550	− .0770	− .1702	.0036	− .0010	.1593	− .0083
355	....	115	45.5	50	05.4	2,889	.7465	− .0685	− .1669	.0017	− .0011	.1593	− .0070
356	....	115	45.3	50	03.4	2,923	.7426	− .0662	− .1657	.0015	− .0011	.1599	− .0054
357	....	115	45.1	50	01.5	2,899	.7431	− .0651	− .1639	.0015	− .0011	.1583	− .0052
358	....	115	45.4	49	59.6	2,883	.7399	− .0671	− .1653	.0015	− .0011	.1584	− .0065
359	....	115	45.5	49	57.4	2,820	.7427	− .0669	− .1630	.0019	− .0011	.1586	− .0036
360	....	115	48.9	49	54.0	2,874	.7362	− .0633	− .1612	.0015	− .0011	.1572	− .0036
361	....	115	47.3	49	54.0	2,792	.7418	− .0654	− .1605	.0016	− .0011	.1575	− .0025
362	....	115	46.0	49	54.5	2,620	.7494	− .0748	− .1640	.0026	− .0010	.1571	− .0043
363	....	115	44.9	49	54.3	2,657	.7496	− .0708	− .1613	.0024	− .0010	.1563	− .0036
364	....	115	39.9	49	59.5	2,980	.7324	− .0654	− .1669	.0023	− .0011	.1600	− .0057
365	....	115	40.5	49	58.5	2,929	.7332	− .0679	− .1677	.0026	− .0011	.1602	− .0060
366	....	115	40.2	49	57.6	2,886	.7353	− .0684	− .1667	.0027	− .0011	.1592	− .0059
367	....	115	41.6	49	56.3	2,835	.7349	− .0717	− .1683	.0030	− .0011	.1596	− .0068
368	....	115	42.7	49	55.8	2,820	.7350	− .0722	− .1683	.0022	− .0011	.1579	− .0093
369	....	115	44.1	49	55.5	2,800	.7395	− .0692	− .1646	.0020	− .0011	.1584	− .0053
370	Kimberly..................	115	58.9	49	41.1	3,661	.6883	− .0184	− .1431	.0020	− .0013	.1512	.0088

PRINCIPAL FACTS FOR GRAVITY STATIONS—*Continued*

No.	Station	Longitude		Latitude		Elevation	Observed Gravity	Free Air Anomaly	Bouguer Anomaly	Terrain	Curvature	T + C (A to 1)	Isostatic
		°	′	°	′	feet							(Airy—40 km.)
371	....	115	43.5	49	52.1	2,578	980.7496	−0.0749	−0.1627	.0027	− .0010	.1553	− .0052
372	....	115	45.0	49	49.8	2,553	.7528	− .0708	− .1577	.0020	− .0010	.1518	− .0049
373	....	115	46.2	49	48.2	2,539	.7536	− .0689	− .1554	.0022	− .0010	.1528	− .0014
374	....	115	46.8	49	45.4	2,885	.7280	− .0577	− .1560	.0012	− .0011	.1513	− .0049
375	....	115	47.7	49	42.4	2,911	.7264	− .0524	− .1515	.0007	− .0011	.1513	− .0006
376	....	115	51.6	49	41.9	3,222	.7112	− .0376	− .1474	.0005	− .0012	.1487	.0006
377	....	115	45.9	49	33.3	2,966	.7155	− .0446	− .1456	.0005	− .0011	.1453	− .0009
378	....	115	48.1	49	34.3	3,010	.7139	− .0436	− .1461	.0008	− .0011	.1461	− .0003
379	....	115	51.7	49	36.2	2,902	.7255	− .0449	− .1438	.0010	− .0011	.1473	.0034
380	....	115	54.2	49	36.9	3,061	.7174	− .0392	− .1434	.0007	− .0011	.1497	.0059
381	Marysville.................	115	57.6	49	38.2	3,100	.7194	− .0354	− .1410	.0017	− .0011	.1506	.0102
382	St. Mary Lake.............	116	10.1	49	36.5	3,201	.6916	− .0512	− .1602	.0116	− .0012	.1539	.0041
383	....	116	16.0	49	37.4	3,217	.6816	− .0610	− .1706	.0160	− .0012	.1548	− .0010
384	....	116	19.0	49	39.1	3,290	.6815	− .0568	− .1689	.0130	− .0012	.1553	− .0013
385	....	116	06.6	49	37.4	3,132	.6949	− .0555	− .1624	.0099	− .0012	.1533	− .0004
386	....	116	03.4	49	37.7	3,142	.6995	− .0507	− .1577	.0060	− .0012	.1515	− .0014
387	....	116	01.7	49	38.1	3,077	.7109	− .0460	− .1508	.0051	− .0011	.1515	.0047
388	....	116	00.1	49	38.1	3,158	.7114	− .0379	− .1454	.0037	− .0012	.1520	.0091
389	....	115	52.3	49	35.2	3,018	.7138	− .0442	− .1470	.0012	− .0011	.1485	.0016
390	....	115	55.9	49	34.6	3,049	.7115	− .0427	− .1466	.0024	− .0011	.1499	.0046
391	....	115	57.5	49	33.5	3,203	.6984	− .0397	− .1488	.0038	− .0012	.1515	.0053
392	....	115	55.5	49	34.9	3,915	.6577	− .0165	− .1495	.0037	− .0013	.1546	.0075
393	....	115	12.6	49	14.1	2,623	.6884	− .0754	− .1647	.0009	− .0010	.1476	− .0172
394	....	115	13.2	49	11.6	2,399	.7040	− .0770	− .1588	.0015	− .0009	.1476	− .0106
395	....	115	14.2	49	12.1	2,406	.7139	− .0673	− .1492	.0016	− .0009	.1479	− .0006
396	....	115	16.8	49	11.9	2,845	.6942	− .0454	− .1423	.0007	− .0011	.1477	.0050
397	....	115	18.3	49	12.2	3,062	.6834	− .0362	− .1405	.0005	− .0011	.1469	.0064
398	....	115	21.3	49	13.1	3,350	.6703	− .0236	− .1377	.0009	− .0012	.1471	.0091
399	Gold Creek.................	115	25.0	49	12.4	3,228	.6812	− .0231	− .1330	.0016	− .0012	.1497	.0171
400	....	115	10.9	49	16.5	2,720	.6934	− .0649	− .1575	.0011	− .0010	.1494	− .0080
401	....	115	09.0	49	17.5	2,880	.6937	− .0510	− .1491	.0013	− .0010	.1485	− .0005
402	....	115	04.1	49	18.0	3,046	.6734	− .0564	− .1601				
403	Morrissey..................	115	00.8	49	23.3	3,139	.6707	− .0582	− .1652	.0079	− .0012	.1505	− .0080

404	Galloway..................	115	12.2	49	21.2	2,849	.6946	− .0584	− .1555	.0019	− .0011	.1473	− .0074
405	Jaffray....................	115	18.1	49	22.2	2,702	.6945	− .0738	− .1659	.0010	− .0010	.1471	− .0188
406	Tokay.....................	115	28.1	49	28.0	2,585	.7210	− .0670	− .1551	.0019	− .0010	.1454	− .0088
407	Ramport..................	115	37.0	49	31.5	2,686	.7242	− .0595	− .1510	.0021	− .0010	.1474	− .0025
408	Eagen.....................	115	42.7	49	33.5	2,930	.7164	− .0474	− .1472	.0012	− .0011	.1468	− .0003
409	....	115	44.2	49	32.4	2,952	.7172	− .0428	− .1434	.0008	− .0011	.1465	.0028
410	Lumberton................	115	52.1	49	25.3	3,236	.6955	− .0273	− .1375	.0023	− .0012	.1501	.0137
411	Fassifern..................	115	50·9	49	27.2	3,261	.7011	− .0222	− .1332	.0015	− .0012	.1488	.0159
412	....	115	47.9	49	29.9	3,056	.7114	− .0352	− .1393	.0018	− .0011	.1482	.0096
413	....	115	40.2	49	35.3	2,770	.7214	− .0601	− .1545	.0011	− .0010	.1532	− .0012
414	....	115	39.3	49	36.1	2,731	.7186	− .0678	− .1608	.0015	− .0010	.1525	− .0077
415	Fort Steele................	115	37.7	49	36.7	2,522	.7285	− .0785	− .1644	.0026	− .0010	.1541	− .0087
416	....	115	36.9	49	37.1	2,714	.7189	− .0706	− .1631	.0026	− .0010	.1539	− .0076
417	....	115	36.0	49	39.7	3,107	.7099	− .0466	− .1524	.0054	− .0011	.1567	.0086
418	....	115	34.2	49	39.7	3,185	.7015	− .0476	− .1561	.0093	− .0012	.1567	.0087
419	....	115	36.9	49	39.3	2,816	.7223	− .0609	− .1568	.0040	− .0011	.1558	.0019
420	....	115	38.0	49	38.3	2,750	.7163	− .0716	− .1553	.0030	− .0010	.1548	− .0085
421	....	115	38.3	49	40.4	2,797	.7197	− .0668	− .1621	.0034	− .0011	− .1570	− .0028
422	....	115	41.3	49	41.9	2,544	.7371	− .0755	− .1622	.0037	− .0010	.1543	− .0052
423	Wasa.......................	115	47.0	49	45.7	2,536	.7492	− .0699	− .1562	.0024	− .0010	.1551	.0003
424	....	115	47.0	49	39.7	2,863	.7204	− .0590	− .1565	.0006	− .0011	.1533	− .0037
425	....	115	44.0	49	37.0	2,781	.7258	− .0572	− .1519	.0008	− .0010	.1507	− .0014
426	....	115	45.1	49	35.4	2,646	.7335	− .0598	− .1499	.0013	− .0010	.1494	− .0002
427	Lake Louise...............	116	12·2	51	25.5	5,051	.7293	− .0007	− .1727	.0046	− .0015	.1755	.0059
428	Great Divide..............	116	18.2	51	27.1	5,330	.7067	+ .0005	− .1810				
429	Field.......................	116	30.1	51	23.7	4,074	.7526	− .0666	− .2054				
430	....	116	34.9	51	17.9	3,697	.7649	− .0814	− .2073				
431	Yoho.......................	116	25.5	51	25.7	4,759	.7212	− .0366	− .1987				
432	Banff......................	115	35.0	51	10.9	4,537	.7584	.0017	− .1529	.0046	− .0014	.1751	.0254
433	Castle Mountain...........	115	54.6	51	15.9	4,693	.7437	− .0059	− .1657				
434	Sawback..................	115	42.1	51	10.1	4,547	.7465	− .0081	− .1630				
435	Massive..................	115	47.3	51	13.2	4,594	.7492	− .0056	− .1621				
436	Hawk Creek...............	116	03.6	51	04.9	4,390	.7266	− .0352	− .1847	.0095	− .0014	.1780	.0014
437	Continental Divide..........	116	02.9	51	13.6	5,386	.6883	.0074	− .1760				
438	....	116	07.6	51	07.7	4,699	.7097	− .0272	− .1873				
439	Kootenay River............	116	02.6	50	53.0	3,845	.7416	− .0538	− .1848	.0036	− .0013	.1750	− .0075
440	....	115	58.7	51	01.5	4,150	.7369	− .0423	− .1837				
441	....	115	58.4	50	56.5	4,128	.7256	− .0485	− .1891				
442	....	115	59.9	50	47.7	3,740	.7312	− .0664	− .1938				
443	....	115	53.8	50	42.1	3,916	.7165	− .0562	− .1895				
444	....	115	56.1	50	40.6	4,853	.6528	− .0294	− .1947	.0085	− .0015	.1710	− .0167

PRINCIPAL FACTS FOR GRAVITY STATIONS—*Continued*

No.	Station	Longitude	Latitude	Elevation	Observed Gravity	Free Air Anomaly	Bouguer Anomaly	Terrain	Curvature	T + C (A to 1)	Isostatic
		° ′	° ′	feet							(Airy—40 km.)
445	....	115 58.3	50 38.8	4,102	980.6903	−0.0602	−0.1999	.0133	− .0014	.1693	− .0187
446	....	116 01.4	50 38.2	3,483	.7215	− .0863	− .2049	.0187	− .0012	.1659	− .0215
447	Kananaskis................	115 07.2	51 05.3	4,231	.7755	− .0018	− .1459				
448	Cochrane..................	114 28.8	51 12.5	3,759	.8136	− .0187	− .1468				
449	Eldon.....................	116 02.6	51 21.5	4,827	.7334	− .0116	− .1761				
450	Temple....................	116 06.0	51 22.4	4,920	.7313	− .0063	− .1739				
451	Bow Pass..................	116 30.0	51 43.5	6,645	.6652	.0592	− .1671	.0052	− .0017	.1803	.0167
452	....	116 17.7	51 33.0	5,975	.6854	.0315	− .1720				
453	....	116 22.6	51 38.6	6,268	.6821	.0474	− .1661				
454	Saskatchewan River.........	116 41.7	51 58.1	4,563	.8005	− .0233	− .1787	.0070	− .0014	.1801	.0070
455	....	116 34.3	51 47.0	5,688	.7200	.0191	− .1746				
456	....	116 39.6	51 51.8	5,464	.7382	.0086	− .1775				
457	....	116 54.5	52 04.3	4,715	.7806	− .0378	− .1984				
458	....	116 49.5	52 00.2	4,706	.7928	− .0202	− .1805				
459	Gatehouse.................	117 12.3	52 12.9	6,583	.6967	.0415	− .1827	.0087	− .0017	.1788	.0031
460	Big Hill Creek.............	117 01.8	52 09.9	5,112	.7688	− .0206	− .1947				
461	Sunwapta Falls.............	117 38.2	52 31.9	4,564	.8447	− .0280	− .1835	.0068	− .0014	.1763	− .0018
462	....	117 20.3	52 20.4	5,161	.7856	− .0148	− .1899				
463	....	117 26.7	52 26.8	5,051	.8064	− .0133	− .1853				
464	Jasper....................	118 05.0	52 52.5	3,483	.9306	− .0738	− .1924	.0046	− .0012	.1668	− .0222
465	....	117 48.2	52 41.2	4,026	.8799	− .0570	− .1941				
466	Leach Lake................	117 54.1	52 46.6	4,070	.8893	− .0515	− .1901				
467	Astoria River..............	118 01.9	52 46.8	4,009	.8958	− .0510	− .1876				
468	Rock Cut..................	117 57.5	53 10.5	3,267	.9961	− .0544	− .1657	.0050	− .0012	.1538	− .0081
469	Hinton....................	117 35.2	53 24.3	3,327	981.0323	− .0324	− .1457				
470	Galloway..................	116 52.1	53 32.4	3,270	.0715	− .0103	− .1217				
471	Edson.....................	116 25.3	53 34.9	3,042	.0997	− .0071	− .1107	− .0001	− .0011	.1148	.0029
472	Edmonton..................	113 31.0	53 31.6	2,202	.1691	− .0121	− .0871	.0001	− .0009	.0798	− .0069
473	Calgary (Library)...........	114 04.2	51 02.5	3,439	980.8304	− .0187	− .1358	.0000	− .0012	.1266	− .0104
474	Morley (1952)..............	114 51.2	51 09.6	4,078	.7951	− .0028	− .1417	.0004	− .0013	.1518	.0092

CANADA
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DIRECTION OF FAULTING IN SOME OF THE LARGER EARTHQUAKES OF 1954-1955

BY

JOHN H. HODGSON AND J. IRMA COCK

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ABSTRACT

Fault plane solutions are presented for twenty-three of the larger earthquakes of 1954-1955.

INTRODUCTION

For several years this Observatory has been producing fault plane solutions by Byerly's method. Two recent papers marked the end of the initial stage of this program. The first of these papers (Hodgson, 1957) reviewed the method, summarized the 65 solutions produced to date, showed that these solutions were self-consistent and discussed their implications to tectonic theory. The second paper (Hodgson and Adams, in press) was a statistical examination of the data on which the first 65 solutions had been based. It was the conclusion of this study that the data from the direct phases P and PKP were reasonably accurate but that those from the reflected phases were not acceptable. This latter conclusion was based partly on the first 65 solutions, but more particularly on the solutions to be presented in the present paper. The conclusion to be drawn from the two review papers is that the techniques of the fault plane project have justified themselves sufficiently that the program should be continued, but without the use of the reflected phases.

The present paper is the first of this second series; it presents solutions for 23 earthquakes which occurred in the period from February, 1954, to July, 1955. The data on which the solutions are based were obtained by means of a questionnaire circulated in September, 1955. We are very much indebted to those seismologists who, by completing our questionnaire, have made this study possible.

In this series of solutions we have had, for the first time, data from all the stations of the U.S.S.R. This has made it possible to obtain well-defined solutions without the use of the reflected phases, and as a result to appraise their accuracy. The technique has been to base the solutions on data from P and PKP only; once the diagrams were established, data from the reflected phases were plotted and checked for consistency. They were found to be inconsistent about as often as they were consistent, indicating random data. The detailed results are shown for each solution and a summary is given in the paper mentioned earlier (Hodgson and Adams, in press). It should be stressed that the data from reflected phases have not influenced any of the solutions given in this paper.

PRESENTATION OF THE DATA

Table I lists the earthquakes for which solutions have been attempted. On three of the dates listed there were two earthquakes; in each case the earlier earthquake has been designated A, the later B. The earthquakes are listed in Table I in two sections, those for which solutions have been obtained and those for which no solution has been possible. In the latter case the reason for the failure has been indicated.

TABLE I

LIST OF THE EARTHQUAKES CONSIDERED

Date	H (G.M.T.)	Epicentre		Focal Depth	Magnitude	Remarks
		φ	λ			
Earthquakes for which solutions have not been obtained						
Feb. 1, 1954...	01:06:54	24½°N	143¾°E	0.00R	7¼	Conflict of Data
June 15, 1954...	13:29:59	5°S	77°W	0.01R	6¾	Conflict of Data
Sept. 17, 1954...	11:03:18	21½°S	177°W	0.03R	7	Conflict of Data
Jan. 5B, 1955...	23:42:03	16°S	167½°E	0.00R	6¾	Insufficient Data
April 5, 1955...	15:09:15	25°N	110°W	0.00R	7	Conflict of Data
May 31, 1955...	09:30:44	27°S	177½°W	0.01R	6¾	Insufficient Data
June 14, 1955...	06:11:18	20°N	107°W	0.00R	7	Insufficient Data
July 6, 1955...	01:54:17	51°N	158°E	0.00R	6½	Conflict of Data
Aug. 6, 1955...	08:31:25	21½°S	177½°W	0.05R	6¾	Insufficient Data
Earthquakes for which solutions have been obtained						
Feb. 19A, 1954...	19:07:48	30°S	177¾°W	0.00R	7	
Feb. 19B, 1954...	21:34:41	12½°N	87½°W	0.00R	6¾	
April 17, 1954...	20:10:37	51½°N	179°W	0.00R	6¾	
April 27, 1954...	10:06:24	6°N	82½°W	0.00R	7	
April 29A, 1954...	10:49:27	28½°N	113°W	0.00R	7¼	
April 29B, 1954...	11:34:34	28½°N	113°W	0.00R	7½	
April 30, 1954...	13:02:37	39°N	22°E	0.00R	7	
May 3, 1954...	15:29:40	51½°N	159½°E	0.00R	6¾	
May 14, 1954...	22:39:26	36°N	137°E	0.03R	7	
July 6, 1954...	08:04:42	46½°N	153½°E	0.01R	6¾	
Aug. 18, 1954...	04:42:20	21½°S	176°W	0.02R	7	
Sept. 13, 1954...	02:09:55	21°S	175½°W	0.02R	6¾	
Sept. 15, 1954...	17:56:08	18°S	178½°W	0.09R	7	
Oct. 3, 1954...	11:18:46	60½°N	151°W	0.01R	6¾	
Jan. 5A, 1955...	17:48:35	16°S	167½°E	0.00R	6¾	
Jan. 13, 1955...	02:03:43	53°N	167½°W	0.00R	6¾	
March 14, 1955...	13:12:04	52½°N	173½°W	0.01R	7	
April 17, 1955...	18:35:27	52°N	159¼°E	0.00R	6¾	
April 19, 1955...	20:24:05	30°S	72°W	0.00R	7	
May 30, 1955...	12:31:41	24½°N	142½°E	0.09R	7¼	
June 2, 1955...	00:18:56	51½°N	180°	0.00R	6¾	
June 20, 1955...	12:07:25	51½°N	180°	0.00R	6¾	
July 16, 1955...	07:07:08	37½°N	27°E	0.00R	6¾	

The data on which the solutions are based are shown in Table II. The notation used is that established in earlier papers of the series (*see* for example Hodgson, 1956, page 173).

ANALYSIS OF THE DATA

In this section solutions will be presented for each of the 23 earthquakes for which it has been possible to obtain them in the form that has been established in the earlier papers of the series. In each case the solution diagram will be given and a table will show the number of observations available and the number of these inconsistent. The reflected phases have not influenced the solutions, and these tables provide the material for the examination of their value.

Earthquake of 19:07:48, Feb. 19, 1954. $\phi = 30°S, \lambda = 177\frac{3}{4}°W$

We have found two possible solutions for this earthquake, differing quite radically from each other, which explain the direct data equally well. We present both solutions.

The first solution is shown in Figure 1. In this solution we have assumed that College is incorrect but that the P_2' dilatations recorded at Alicante and at Cartuja, and the P_1 separation between Ottawa and Seven Falls, are correct and have obtained a solution accordingly. The score for this solution is shown in Table III.

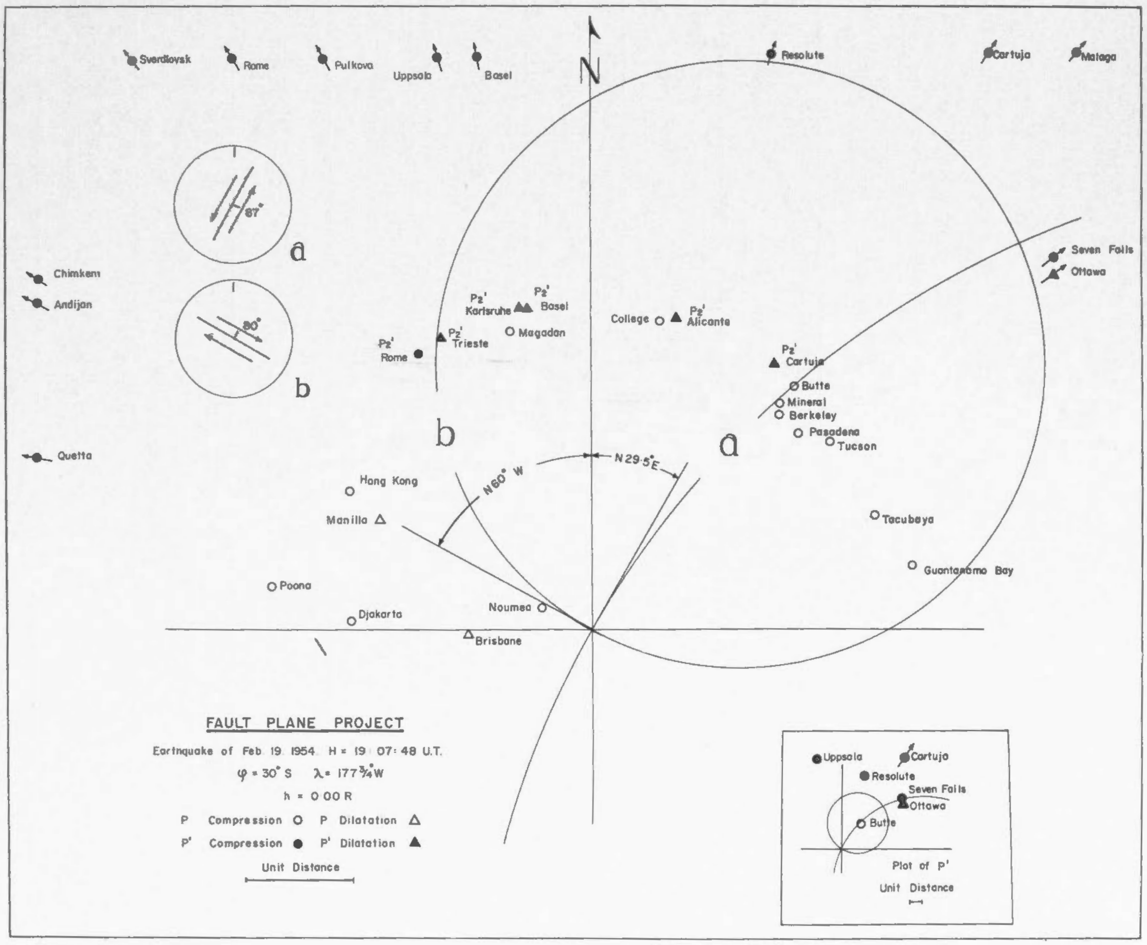

FIGURE 1.

TABLE II

Data on which the Solutions are Based

STATION	Feb. 19A, 1954	Feb. 19B, 1954	April 17, 1954	April 27, 1954	April 29A, 1954	April 29B, 1954	April 30, 1954	May 3, 1954	May 14, 1954	July 6, 1954
Aberdeen			C DD				D			(D)
Alicante	C_1' D_2'	C DD	D DD	(C) CC	(D)	C DD	C	D	C	(D)
Almeria										
Andijan	C_1' CCC						D			C
Apia							D_1'			
Ashkhabad			D					C	D	C
Astrida										
Athens								D	C	C
Balboa Heights		(D)		D						
Bandong								D	C cC	
Barcelona							C			
Barrett										
Basel	C_1' D_2'	C	C		C	(D)	D		D (cC)	C
Berkeley	C	D PcP=D	D CC (CCC) PcP=C	C DD	C	C	(C) CC	C	D dD	(C)
Besancon	(D_1')	(D)	(D)				D	D	D	
Bogota	(DD)	C	D	C		D	D	(CC)	CC	
Bologna										C
Bombay			D	(C_1')		DD	D	C	C	
Boulder City	C	C	D	C	D	D	D	C	D	C
Bozeman					D	D				D
Brisbane	(D)		(D)				(C_1')	D (PcP=C)	C	
Budapest										
Butte	C (CC)	C	(C)	C	D	D	D		D	(C)
Calcutta	DD		D			C_1'	D	D	C	(D)
Cartuja	C_1' D_2' CC dD_1' (dDD)	(D) DD	C (CC) (dDD)	(C) CC PcP=C	C DD (DDD)	C DD (DDD) PcP=C	(D) cC (DD)	D DD	C (DD) dD dDD	C (CC)
Chicago			D	C						
Chihuahua			D	C		(D)				
Chimkent	C_1'									C
Chinchina		D				D	D			
Christchurch							(C_1')		(D)	
Cleveland		C	D	C			D			C
Coimbra					(D)		C			(D) DD
College	(C) CC	C	C	C	C	C	D	C	(C)	D
Columbia		C		C	C	C	D			C
Copenhagen			(D)	D			D	C	D	C
Dehra Dun			D				(C)	(D)		(D)
Djakarta	C	(C_1') (C_2') CC (CCC)	D CC						C cC	C
Erevan			D				D	C	D	C
Fayetteville							D		D	
Fergana										
Frunse			D					C		C

TABLE II—*Continued*

Data on which the Solutions are Based—*Continued*

Aug. 18, 1954	Sept. 13, 1954	Sept. 15, 1954	Oct. 3, 1954	Jan. 5A, 1955	Jan. 13, 1955	March 14, 1955	April 17, 1955	April 19, 1955	May 30, 1955	June 2, 1955	June 20, 1955	July 16, 1955
(C'_1)	....	....	(DD) DDD	DD	....	....	D	C	D CC	(D)	....	C DD
(C'_1) (CC)	D'_1 DD	D'_1 (D'_2)	(C)	D'_1	C	C	(D)	C	C (CC)	C DD	D CC	(C) C C
....	....	....	....	D'_1	....	C	(D)	C	cC	(D)	....	D
....	....	....	....	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....	....	....	....
C	....	(D)	(dD)	....	....	....	....	....	....	....	....	....
D	....	C	D	....	....	D	....	....	....	....	....	....
....	....	....	....	....	....	....		....	C'_1 (CC) (cCC)	....	....	....
D'_1	....	C'_1	D	....	....	....	(D)	....	(D)	....	....	....
....	....	....	....	....	....	....	....	....	....	....	....	....
D (DD)	D (cC)	C	....	D	....	....	....	....	....	....	....	....
DD	....	....	D	....	....	....	....	....	cC D	....	....	D
D'_1 cC'_1	D'_1 cC'_1	C'_1	D	D'_1	C	C (dD)	C	....	C (dD) (CC)	(D)	D	D
C CC (dD)	D CC	C (PcP=C)	C	....	C	C PcP=D	....	C	D (DD) (cC)	D	D	C
.... D'_1 D'_1	D'_1 DD	C'_1 D'_1	D D D	CC D'_1	C (D)	....	....	D	....	(D)	....	D
C D D cC	D C (C)	C D (D)	C C C	.... D	(D) D CC	C (D) D	C D	C	D (C) C (cC) (PcP=D	C (D) (C) PcP=D	D D D (DD) (PcP=C	D C (D'_1)
D	....	(C'_1) D	C	....	C	(D)	....	(D)	(C)	(D)	(C)	C
D D'_1 (C'_2) (CC) cC'_1 dDD	D'_1 (C'_2) (CC) cC'_1 (cC'_2) (DDD)	D'_1 C'_2 (CC) (cCC) (CCC)	(C) (DD) DDD PcP=D	C'_2 C'_2 (CC)	(D) C CC (CCC)	(D) cC (cCC)	C (dD) CC PcP=C	C (CC) CCC	C (CC) (CCC) dDD	C DD cC (cCC) CCC	(C) (DD)	(C) (DD) DDD PcP=D
....	....	....	....	....	....	C	....	C	....	C		
....	D	....	....	....	....	....	....	....	....	....	....	....
D'_1	....	....	(C)	DD	C	D	....	....	....	C	D	
D	D	D	....	C	....	....	....	D	D			
....	....	....	C	....	D	C dD	C	D	(C)	C	D	
(C'_1)	D'_2	D'_1	D	....	....	....	....	C	....	C	D	D
(C'_2)	DD (CCC)	(D'_2) DD	....	....	....	....	....	....	....	....	....	(DD)
D (C'_1) D'_1	C .... D'_1	C	D D D	C	D C D	C C	D C C	D'_1	D .... C DD (dD)	.... C C	(D) .... D	(D) D C
....	....	....	....	....	....	....	....	....	....	....	....	....
D (DD) dD	D (cC)	....	DD	D	C	dD	....	....	C	....	....	D
(C'_1)	....	....	D	....	....	....	....	....	....	....	....	....
D	(D)	D	....	....	....	(D)	....	....	....	....	D	
....	....	....	....	....	C	....	C	....	C	C	....	D
....	D'_1 DD	C'_1	D	....	....	....	....	....	C			

TABLE II—*Continued*

Data on which the Solutions are Based—*Continued*

STATION	Feb. 19A, 1954	Feb. 19B, 1954	April 17, 1954	April 27, 1954	April 29A, 1954	April 29B, 1954	April 30, 1954	May 3, 1954	May 14, 1954	July 6, 1954
Galerazamba										
Gharm			D CC	DD				C	D (dD)	
Goris										
Grozny								C		
Guadalajara		C								
Guantanamo Bay	C		D CC DDD	D	(D) DD	(CC)	D (DD) DDD		CC	
Halifax								C	D	C
Helwan	(D'_1)							D	C	
Hong Kong	C		D (DD)				D (CCC)	C	C	C
Honolulu			(D)						(C)	
Hungry Horse		C		C	D	(C)	D	C	D	
Hyderabad	(DDD)		D				D	C	C	C
Irkutsk			D				D	C	D CC	C
Jersey						C	C		C	
Jujhno-Sakhalinsk			(C)	C	(D)			C	C	
Kabansk			D				D	C	D	C
Kalocsa							C			
Karlsruhe	D'_2			D		(D)	(C)	C	D	C
Kew			C	D cC	C CC	C CC	D	(D)	D (DD) dD	C (CC)
Khorog										C
Kirkland Lake		C		C			D		D	C
Kiruna	C'_1 (DD)		DD (DDD)	D (DD)	(D)	(D)		C	D DD	C
Kodaikanal			(C)					C	C	
Ksara	C'_1 DD	(CC)		C					D cC	
Kulyab	C'_1		D				D	C	D	
Kurilsk								C		
Kyakhta			D				D	C (CC)	D	C CC
La Paz		(C) (DD)	(DD)	C (CC) (PcP=C)	CC	D (DD) (PcP=C)	D DD		D'_1 (DD)	
Lembang	C (CC)	(C'_1)	D CC		C'_1	C C'_1	D	D	C (CC) cC dDD PcP=C	C
Lincoln	DD									
Lisbon			C		D	D PcP=D	C			(D)
Logan										
Lwiro			D'_1 CC (CCC)	C'_1	C'_1 (CC)	C'_1 (CC)	(D)			C'_1
Lwow	C'_1		(C)					D (PcP=C)	(C) (DD) dD	

TABLE II—*Continued*

Data on which the Solutions are Based—*Continued*

Aug. 18, 1954	Sept. 13, 1954	Sept. 15, 1954	Oct. 3, 1954	Jan. 5A, 1955	Jan. 13, 1955	March 14, 1955	April 17, 1955	April 19, 1955	May 30, 1955	June 2, 1955	June 20, 1955	July 16, 1955
(CC)	...	...	(C)	...	...	...	...	...	...	...	...	...
...	...	...	(C)	...	...	...	...	...	C	C	...	D
...	...	...	CC									
...	D'_1	(D'_1)	...	...	C	...	...	...	C	C	D	
	D'_2	(D'_2)	...	...	...	...	...	...	...	PcP=C		
...	...	...	...	...	...	...	...	...	...	...	...	...
C	...	...	...	...	...	...	...	...	...	...	...	...
CC	(CC)	...	D	...	...	...	...	...	CC	C	(C)	D
...	...	...	CCC	...	...	...	...	...	...	...	(CCC)	CC
...	...	(C'_1)	(C)	...	D	...	...	...	...	...	...	...
(C'_1)	...	(D'_1)	(C)	...	...	...	(D)	...	(D)	(D)	(C)	
D	D	...	D	(C)	...	...	C	...	C	D		
...	...		...	(CC)								
C	C	D	(D)	...	D	...	...	...	(C)	...	D	...
(C)	D	C	(D)	(D)	C	C	C	C	D	C	C	C
D	...	C	D	CC	C	C	C	CC	C	C	(C)	(C)
D	D	C	...	D	C	C	...	...	C	C	...	D
...	...	...	...	...	DD	(dD)	...	...	cC			
...	...	...	D									
D	D	C	...	...	...	C	C	...	(D)	C	C	D
(cC)	...	(CC)										
D	D	C	D	D	C	...	C	...	C	C	C	D
...	...	...	...	...	...	...	...	...	...	...	...	...
cC'_1	D'_1	C'_1	D	D'_1	C	C	C	...	C	(D)	D	C
			dD	...	PcP=C	(dD)	...	...	cC	(PcP=D)	(PcP=C)	
C'_1	D'_1	C'_1	D	(CC)	D	(D)	(D)	(D)	(C)	C	(C)	D
C'_2	(dD'_1)	...	...	CCC	...	DD	...	(CC)	CC	PcP=C	(PcP=C)	
...	...	...	...	...	...	(DDD)	...	...	cC			
									CCC			
...	...	...					...		...	...	...	...
...	...	...	D	...	D	C	...	D	(C)	C	D	D
									(cC)			
									cCC			
cC'_1	D'_1	C'_1	D	C'_1	D	C	C	(CC)	D	C	D	
...	DD	...	cCC	...	(PcP=D)	cC	...	...	(dD)			
	(dD'_1)	...	...	...	...	PcP=C	...	...	cCC			
...	...	...	...	D	...	...	...	...	C	...	(C)	(C)
...	D'_1	C'_1	D	C'_1	C	...	C	DD	(D)	C	(C)	(C)
...	CC	DD	(DD)	DD								
	(cC'_1)											
D'_1	...	...	D	...	C	C	C	...	C	...	...	D
			(DD)	...	...	...	...	...	...	...	...	(DD)
			DDD									
...	...	...	...	...	...	C	C	...	C	C	C	...
											dD	
D	D	C	D	D	C	C	...	...	C	C	C	D
C	C	...	CC	...	D	D'_1	D'_1	(C)	D'_1	C'_1	(DD)	(DD)
DD	(CC)	...	...	...	DD	DD	DD	(CC)	CC	(CC)		
cC	cC											
(cCC)	(cCC)											
D	D	C	(cCC)	D	...	(dD)	...	...	(D)	...	...	...
dD	(DD)	(CC)										
(DD)	(cC)	CCC										
...	...	...	...	...	...	...	...	...	...	...	...	...
D'_1	D'_1	C'_1	D	...	C	...	...	(D)	(C'_1)	...	D	D
(CC)	...	DD										
					C	C	...	...	D	C		
						(cC)	...	...	(DD)			
									(cC)			
...	D'_1	(C'_1)	...	D'_1	(D'_1)	(C'_1)	C'_1	...	...	C'_1	(C'_1)	(D)
...	dD'_1	cC'_1	...	CC	(CC)	...	...	...	...	(CC)	(C'_2)	(CC)
...	(DD)	...	...	...	...	...	...	...	...	...	CC	CCC
...	(C'_1)	(D'_1)	D	...	C	C	...	...	...	(D)	(C)	...
...	DD	(DD)	(DD)	...	(DD)	...	...	...	...	(CC)	CC	
					DDD	...	...	...	...	...	DDD	
											PcP=D	

TABLE II—*Continued*

Data on which the Solutions are Based—*Continued*

STATION	Feb. 19A, 1954	Feb. 19B, 1954	April 17, 1954	April 27, 1954	April 29A, 1954	April 29B, 1954	April 30, 1954	May 3, 1954	May 14, 1954	July 6, 1954
Magadan	(C)		D	(D)	(D)			(C)		
Makhach-Kala	C_1'		D	D_1'				C	D	C
Malaga	C′ (CC)	C	(D)	(C)	D		(D)		C	
Manilla	(D)		(C)				D	(D)	C	C
Manzanillo		(D)								
Melbourne							(DD)			
Merida				(D)						
Miami					(D)					CC
Mineral	C	C		C	D	D	D (DD)	C	D	D
Moscow	C′							C	D	C
Mount Hamilton	C		D	C	C	D	D CC	D	D	D
Myrgab										
Narin	C_1' CC		D				D	C	D	C DD
Nelson	C DD	C PcP=D	D	C	D	D	D (DD)	C	D	C
Neuchatel										
New Delhi			(C)				D	C	D	
Noumea	C CC (DDD)		C (CC) (PcP=D)					D (DD) (PcP=C)	(D) (dD) CCC	C CC dD
Oaxaca				C	(C)	D				
Obi-Gharm			D				D (CCC)	C	D (PcP=D	C
Ottawa	D_1'	C	C	C	C	C	D	(D)	D	(D)
Palisades		C	(D)	C DD	C (CC)		D	C	D CC (cC)	C
Palomar										
Paris										
Pasadena	C	C	D	C	D	D	D (DD)		D	D
Pavia			D					(C)	D	C
Perth									C	C
Petropavlosk			(C)	C	(D)		D (DD) DDD	(C)	D (cC) DD	
Philadelphia		(D)								
Poona	C	(C_1')	D	D_1'	C_1'	C_1'	(C)	C	C	C
Prato							C			
Puebla		C		C		C				
Pulkovo	C_1'		D DD CCC					C DDD	D dD DDD	C
Quetta	C_1'	D_1'	(C)	D_1'		C_1'	D	C	(C)	C cC
Rapid City										
Rathfarnham			C	(C)	(C) (DD) PcP=C	(C) (DD) (PcP=d)	D (DD)		D (cC)	C
Reggio Calabria										

TABLE II—*Continued*

Data on which the Solutions are Based—*Continued*

Aug. 18, 1954	Sept. 13, 1954	Sept. 15, 1954	Oct. 3, 1954	Jan. 5A, 1955	Jan. 13, 1955	March 14, 1955	April 17, 1955	April 19, 1955	May 30, 1955	June 2, 1955	June 20, 1955	July 16, 1955
D	....	C	C	....	....	D	(C)	....	C	C	C	D
dD												
D'_1	....	....	....	....	....	....	....	....	....	....	....	....
D'	D'	(C')	....	(D')	....	(D)	(D)	(D)	....	C	D	D
DD	(CC)	(CC)										
D	....	C	....	D	(D)	(D)	....	....	C	D	D	....
....	....	....	....	....	....	....	....	....	....	....	....	....
D	C	D	....	....	....	....	....	....	C	....	....	....
....	....	....	....	....	(D)	C	....	....	....	....	D	....
(DD)	DD	....	....	....	(D)	....	....	....	....	C	(C)	D
(CCC)	....	....	....	....	(DDD)							
C	D	....	C	C	C	C	....	C	D	(D)	....	C
cC	cC											
D'_1	D'_1	C'_1	D	(DD)	C	C	....	....	C	C	D	C
	DD	DD	dD	....	....	CC						
	CCC											
	cCC											
C	D	C	C	C	(D)	C	C	C	D	D	D	(D)
....	....	(dD)	....	....	....	....	....	....	(cC)	....	....	....
....	....	....	....	....	C	C	....	....	C	C	....	....
D'_1	D'_1	C'_1	D	....	....	....	....	....	....	....	....	....
....	(DD)											
C	D	C	C	C	C	C	C	C	D	C	D	D
....	....	....	D	....	....	....	....	....	....	....	....	D
....	....	....	D	....	C	C	C	CC	C	....	....	....
D	D	cC	(CC)	C	CC	D	CC	CC	D	D	D	(D'_1)
dD	....	....	CCC	(PcP=C)	DDD	dD	....	(CCC)	CC	(DD)	DD	CC
....			....	....	(PcP=C)	....	....	....	(cC)	(PcP=C)	cC	(CCC)
									(PcP=C)	....	cCCC	
											(PcP=C)	
C	....	....	D	....	D	....	....	....	....	....	D	....
CC												
D'_1	CC	C'_1	D	....	....	C	....	D'_1	C	....	(C)	....
D'_1	....	D'_1	D	C'_1	D	....	D	D	D	C	D	(C)
(C)	C	DD	D	(CC)	C	C	C	C	CC	C	D	D
(DD)	CC	....	(CC)	....	(cC)	cC	cC					
cC	....	....	dD									
(cCC)												
....	....	....	....	....	....	....	....	....	D	....	....	....
D'_1	D'_1	C'_1	D	D'_1	....	C	C	....	C	C	D	D
C	D	C	D	....	....	C	....	C	D	C	....	....
....	cC	....	....	....	....	....	....	....	(cC)			
D'_1	D'_1	....	D	D'_1	(D)	C	....	....	C	C	D	D
	(dD'_1)	....	....	....	....	cC						
D	....	....	....	D	C	....	D	....	....	....	D	....
					(CC)							
D	....	C	C	....	....	(D)	C	....	....	C	C	....
....	....	....	....	....	....	C						
....	D'_1	....	D	D	D	D	(D)	D'_1	(D)	(D)	....	D
....	....	C'_1	....	....	(D)	....	....	....	....	....	(C)	D
....	....	....	....	....	....	C	....	....	....	....	....	....
D'_1	....	....	D	....	C	C	....	....	C	....	....	....
CC	....	....	dD	....	....	....	....	....	(dD)			
....	....	....	DDD	....	....	....	....	....	(CC)			
....	(C'_1)	C'_1	D	(C)	C	D	(D)	D'_1	....	....	....	....
....	....	....	....	....	....	(dD)						
D	....	....	....	....	....	....	....	....	....	....	....	....
D'_1	....	C'_1	D	....	....	C	D	C	D	C	D	D
....	....	....	(DD)	....	....	cC	(PcP=D)	(CC)	CC	CCC		
....	....	....	dD	....	....	....	....	....	CCC	PcP=C		
			cCC	....		....	....	....	cCC			
			(PcP=C)									
....	....	....	....	D'_1	....	....	....	....	....	....	....	....

TABLE II—*Continued*

Data on which the Solutions are Based—*Continued*

STATION	Feb. 19A, 1954	Feb. 19B, 1954	April 17, 1954	April 27, 1954	April 29A, 1954	April 29B, 1954	April 30, 1954	May 3, 1954	May 14, 1954	July 6, 1954
Resolute	C'_1	C	...	C	D	D	D	C	D	C
Reykjavik	...	...	...	D	D	D	C	(D)	(D)	C
Riverside	...	...	...	...	...	...	...	...	...	...
Riverview	...	...	C	...	...	...	(C'_1)	...	C	D
							CC	...	...	CC
							(CCC)	...	...	...
Rocca di Papa	...	...	...	...	...	...	...	...	D	...
Rome	C'_1	...	(C)	D	...	...	...	(C)	D	C
	C'_2	...	...	CC	...	...	...	...	...	...
	(DD)	...	...	...	...	...	...	...	...	...
Salo	...	...	...	...	...	...	C	D	...	(D)
								DD	...	DD
								DDD	...	...
Salt Lake City	...	...	...	...	D	D	...	...	D	D
San Juan	...	C	C	D	...	C	C	...	D'_1	...
Scoresby-Sund	...	...	...	C	...	...	D	C	C	C
Semipalatinsk	...	...	...	...	...	...	...	...	...	...
Seven Falls	C'_1	C	(D)	C	C	...	...	...	D	(D)
Shasta	...	...	D	C	D	(C)	(C)	C	D	D
							(DD)	DD	(cC)	(cC)
Shawinigan Falls	...	(D)	...	C	...	...	...	...	D	...
Shemakha	...	...	...	D'_1	...	...	D	C	D	...
Shillong	C'	...	C	...	...	...	D	C	(C)	C
Sitka	...	...	D	C	...	...	...	...	D	...
Stalinabad	C'_1	...	D	D'_1	...	...	D	...	D	...
									(PcP=D)	...
State College	...	C	C	C	...	C	(C)	...	D	C
							CC	...	(DD)	
							DDD			
Strasbourg	...	C	(D)	D	...	...	CC	C	D	C
								PcP=D	...	...
Stuttgart	...	...	C	...	...	...	...	C	D	C
			PcP=D	...	...	...	...	...	...	...
Sverdlovsk	C'_1	...	D	...	...	...	...	C	D	C
Swan Island	...	...	...	...	...	...	...	...	...	...
Szeged	...	...	...	...	...	...	C	...	...	...
Tacubaya	C	C	D	C	C	C	...	...	DD	...
Tananarive	...	...	D'_1	...	...	C'_1	D	...	...	(CC)
Tashkent	...	...	D	...	...	...	...	C	...	C
Tbilisi	C'_1	...	D	...	...	...	D	C	D	C
Tinemaha	...	...	...	...	...	...	...	...	...	...
Trieste	(D'_1)	...	(C)	...	(D)	(D)	C	(C)	D	...
	D'_2	...	...	...	(DD)	CC	...	...	...	...
	(DD)	...	...	...	...	...	...	...	...	...
	DDD	...	...	...	...	...	...	...	...	...
Tucson	C	D	(C)	C	D	...	(C)	...	D	C
Uccle	...	...	...	...	...	...	...	...	D	C
Uglegorsk	...	...	(C)	C	...	...	...	C	C	D
Ujhgorod	...	...	...	...	...	...	D	D	D	...
Uppsala	C'	(CC)	C	CC	C	C	D	C	D	C
					CC	...	...	cC	...	...
Uvira	...	...	...	...	...	...	...	...	C'_1	...
Vera Cruz	...	...	...	...	C	(D)	...	...	...	...
Victoria	...	C	D	C	D	...	...	...	D	...

TABLE II—*Continued*

Data on which the Solutions are Based—*Continued*

Aug. 18, 1954	Sept. 13, 1954	Sept. 15, 1954	Oct. 3, 1954	Jan. 5A, 1955	Jan. 13, 1955	March 14, 1955	April 17, 1955	April 19, 1955	May 30, 1955	June 2, 1955	June 20, 1955	July 16, 1955
… (C_1') eC_1'	… … …	… D_1' (dD_1')	D (DD) dD D …	… …	(C) … …	… … …	… … …	… … …	… (C) (cC)	… (D) …	… (C) …	… C …
… D (DD) (dD) (CCC)	… D (dD) CC	… D (cC) …	… C (CC) …	… D (cC) …	… D …	… … … …	… … … …	… D (DD) …	D (D) DD (dD)	… D … …	… D (DD) (dD)	… …
… D_1' eC_1' … … … …	… D_1' DD eC_1' … … …	… C_1' C_2' (CC) … … …	(D) D … D (DD) …	… D_1' DD … D_1' (DD) …	C C CC eC (D) (DD) …	… C (dD) … … … …	… C … … (D) … …	… D DD … … … …	… C DD (dD) (D) DD (dD)	… C … … …	… D (DD) (dD) …	… D …
D … (C_1') … D_1' C CC (dD)	… … (C_1') … … D … …	… D_1' … … … (C) cC PcP=D	… D (C) … … C …	… … … … C_1' (D) …	C C … … D C …	(D) C (D) … C C (CC)	(D) … (C) … D (D) …	… C … … D C …	(C) … D C D D (cC)	(D) C (D) C … C	C (C) … D … D	C D … D (C) C
… D (DD) …	… D_1' (DD) …	… C_1' (CC) C	D … (C)	… … (C)	D … C	… … (D)	… … C	… … …	… … …	… … C	… … D	… … D
… D_1' … …	… D_1' CC (DD)	… C_1' …	… D (C)	… … …	… (D) C	… C (D)	… … C	… … D	… C D	… (D) …	… (C) …	… … …
D_1' …	D_1' (dDD)	C_1' C_2'	D dD	C_1' …	… …	C …	C …	(CC) …	C (dD)	C …	D (dD) DDD	D
D_1' …	D_1' …	C_1' C_2'	D dD	… …	… …	C …	C …	… …	(D) (dD) DD	C …	D (dD)	C
… (D) CC	D (D) CC	C_1' …	D (C)	… …	C …	D …	C …	… …	(D) …	… …	D (CCC)	(C) CC
… C D_1' DD D_1' (C_1')	… (D) (C_1') D_1' D_1'	… (C) (C_1') (D_1') …	… D (C_1') D D	… … … D …	… (D) … C C (PcP=D)	… C … C C …	… … … C C PcP=C	… … … … …	… … C C C	… … C C C	… … D_1' D …	… … (D) D (C)
… D_1' … … …	… (C_1') … … …	… … … … …	… D … … …	… D_1' D_2' (DD) …	… C (DD) … …	… C … … …	… C … … …	… C (C_1') (CC) CCC	D C	… C	… D	… D DD
C	C	C	D	C	C	C	…	C	D (DD)	C	D	…
… D (PcP=C) …	… … … …	… C … …	… C DD …	… … … …	… C … …	… … … …	… C … …	… … … …	… C … …	… C … …	… C dD …	D D (DD) …
DD …	… …	DD …	D …	… …	D (DD)	C …	C …	… …	D DD (dD) DDD	C … …	D CC PcP=D	C
… C C	… … …	… … C	… … C	… … …	… (D) …	… … …	… … …	… … …	… (CCC) D	… … C	… … C	… … C

TABLE II—*Concluded*

Data on which the Solutions are Based—*Concluded*

STATION	Feb. 19A, 1954	Feb. 19B, 1954	April 17, 1954	April 27, 1954	April 29A, 1954	April 29B, 1954	April 30, 1954	May 3, 1954	May 14, 1954	July 6, 1954
Vienna							D	D	(C)	(D)
Vladivostok				C			D			
Washington		C		C	C	C	D	(D)	(C)	
Wellington									C (CC)	
Woody										
Yalta										C
Zurich			D				D	C	D	C

TABLE II—*Concluded*

Data on which the Solutions are Based—*Concluded*

Aug. 18, 1954	Sept. 13, 1954	Sept. 15, 1954	Oct. 3, 1954	Jan. 5A, 1955	Jan. 13, 1955	March 14, 1955	April 17, 1955	April 19, 1955	May 30, 1955	June 2, 1955	June 20, 1955	July 16, 1955
(C_1')	(C_1')	(D_1')	(C)	(C_1')	C	....	(D)	....	(D)	....	D	(D)
					PcP=C	....	....	....	DD			
....	D	C	....	....	....	....	....	....	C	....	....	D
									dD			
....	(D)	....	D	....	....	....	C	C	....	C	....	D
D	D	D	....	C	....	....	....	(C)	D	....	....	....
....	....	....	....	....	....	....	....	....	D	C	D	....
....	....	....	....	....	....	....	....	....	....	....	....	....
....	....	C_1'	D	D_1'	C	C	C	....	C	C	D	D
		cC_1'	....	....	....	....	....	....	cC			

TABLE III

	Direct Phases				Reflected Phases					Grand Total
	P	P_1'	P_2'	Total	PP	pPP	pP_1'	PPP	Total	
Total Number of Observations	19	27	6	52	15	1	1	4	21	73
Number of Inconsistent Observations..................	5	3	0	8	7	1	0	2	10	18

The alternative solution is shown in Figure 2, and the score is given in Table IV. This solution supposes the field to be compressional, so that Ottawa is made inconsistent,

TABLE IV

	Direct Phases				Reflected Phases					Grand Total
	P	P_1'	P_2'	Total	PP	pPP	pP_1'	PPP	Total	
Total Number of Observations....	19	27	6	52	15	1	1	4	21	73
Number of Inconsistent Observations..................	2	4	2	8	5	1	0	1	7	15

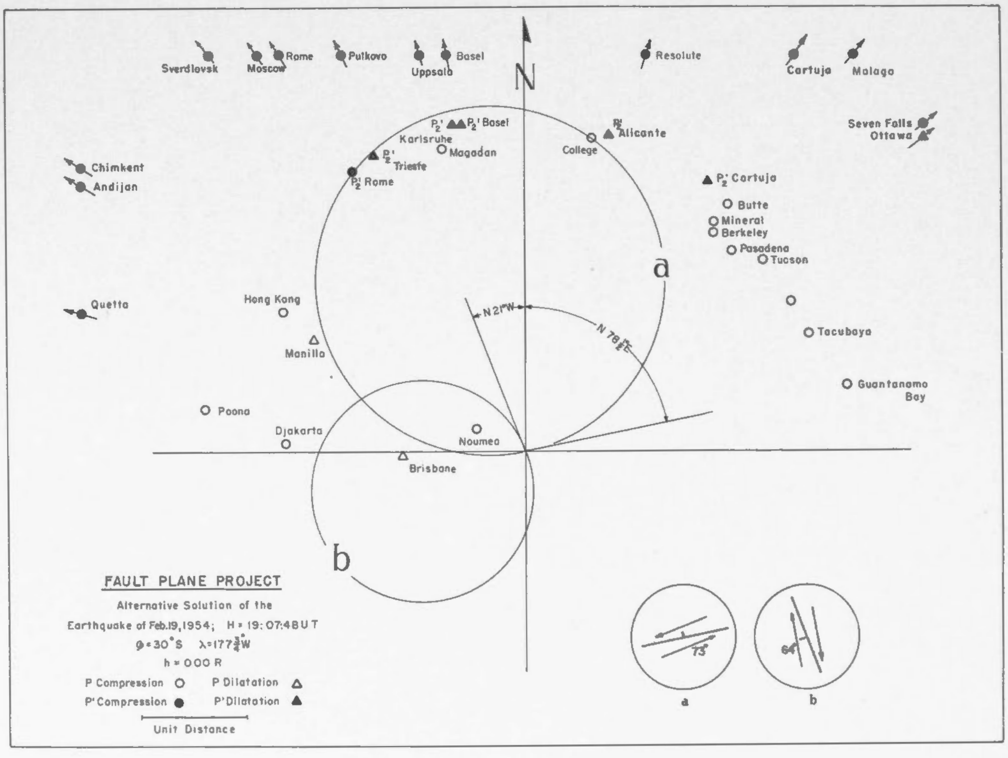

FIGURE 2.

and gives the solution in terms of a smaller pair of circles. As shown in Tables III and IV the score for the direct phases is the same in each case, whereas Figure 2 scores better on the reflected phases. Despite this better score we prefer the solution shown in Figure 1 because the null vector points in the direction we have come to anticipate. For this reason the inconsistencies listed in Table II are those associated with Figure 1.

Earthquake of 21:34:41, Feb. 19, 1954. $\phi = 12\frac{1}{2}°N$, $\lambda = 87\frac{1}{2}°W$

The solution for this earthquake is shown in Figure 3 and the score is given in Table V. The earthquake is not large, and the percentage of inconsistencies is consequently higher

TABLE V

	Direct Phases				Reflected Phases				Grand Total
	P	P'_1	P'_2	Total	PP	PPP	PcP	Total	
Total Number of Observations..........	36	4	1	41	6	1	2	9	50
Number of Inconsistent Observations.....	7	3	1	11	3	1	0	4	15

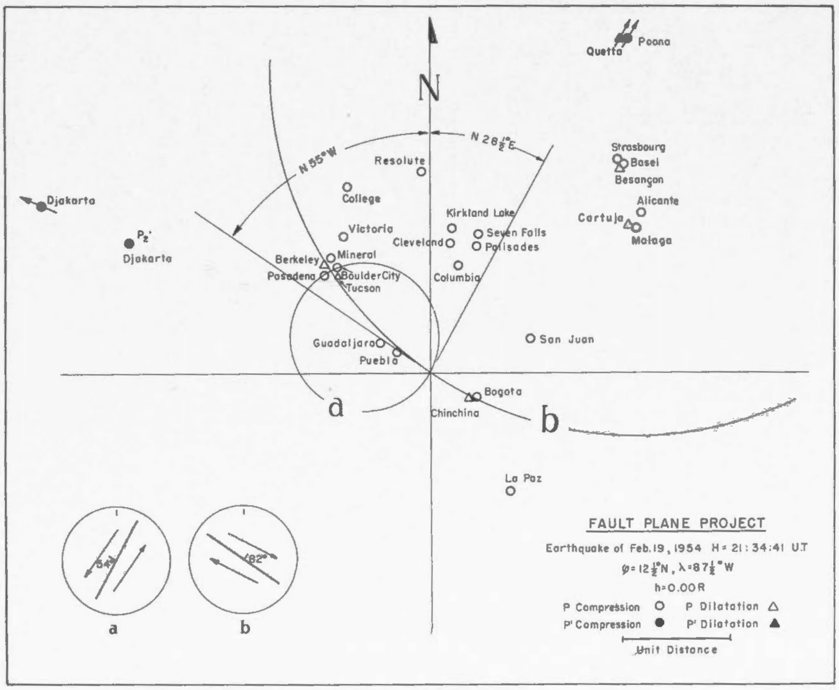

FIGURE 3.

than normal, but the solution must be approximately correct. The most serious criticism of the solution is the poor score shown for the PKP observations, 4 out of 5 having been made inconsistent. However all of these observations were described as weak, and it seems better to sacrifice them rather than some of the nearer observations.

Earthquake of 20:10:37, April 17, 1954. $\phi = 51\frac{1}{2}°N$, $\lambda = 179°W$

This earthquake is another with a magnitude of $6\frac{3}{4}$, a little too small for a satisfactory solution. As a result there is a good deal of ambiguity, and we have found two possible solutions, which explain the data about equally well.

The first solution is shown in Figure 4, and the score is given in Table VI. This solution has a slightly better score on the direct phases, and many of the observations made inconsistent in this solution have been described as doubtful by our collaborators.

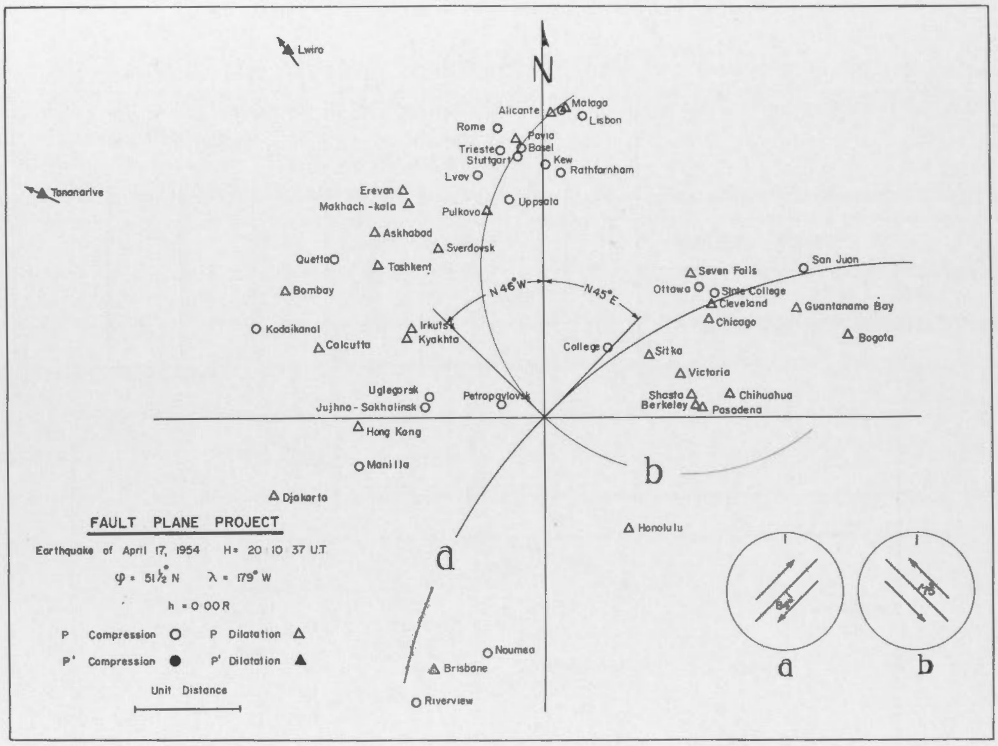

FIGURE 4.

TABLE VI

	Direct Phase			Reflected Phases					Grand Total
	P	P'	Total	PP	PPP	pPP	PcP	Total	
Total Number of Observations..........	77	2	79	14	5	1	3	23	102
Number of Inconsistent Observations.....	19	0	19	4	3	1	1	9	28

The alternative solution is shown in Figure 5, and the score is given in Table VII.

Because the solution shown in Figure 4 has the fewer inconsistencies, we have used it as the solution in marking the inconsistencies in Table II.

TABLE VII

	Direct Phases			Reflected Phases					Grand Total
	P	P$'_1$	Total	PP	PPP	pPP	PcP	Total	
Total Number of Observations..........	77	2	79	14	5	1	3	23	102
Number of Inconsistent Observations.....	22	0	22	7	5	0	2	14	36

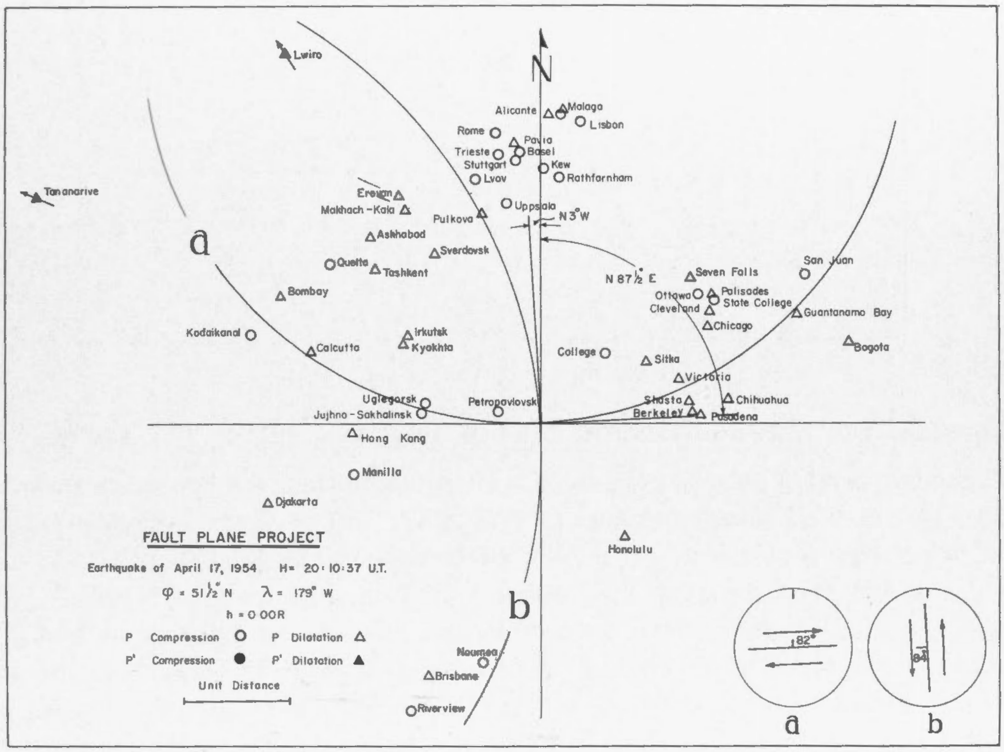

FIGURE 5.

Earthquake of 10:06:24, April 27, 1954. $\phi = 6°N$, $\lambda = 82\frac{1}{2}°W$

This earthquake presented no problems; the solution is shown in Figure 6 and the score is given in Table VIII. It will be noted that the score is remarkably good; this undoubtedly reflects the fact that almost all stations in North America received an unambiguous recording of the earthquake.

TABLE VIII

	Direct Phases			Reflected Phases				Grand Total
	P	P$'_1$	Total	PP	pP	PcP	Total	
Total Number of Observations............	52	7	59	9	1	2	12	71
Number of Inconsistent Observations......	6	1	7	4	0	1	5	12

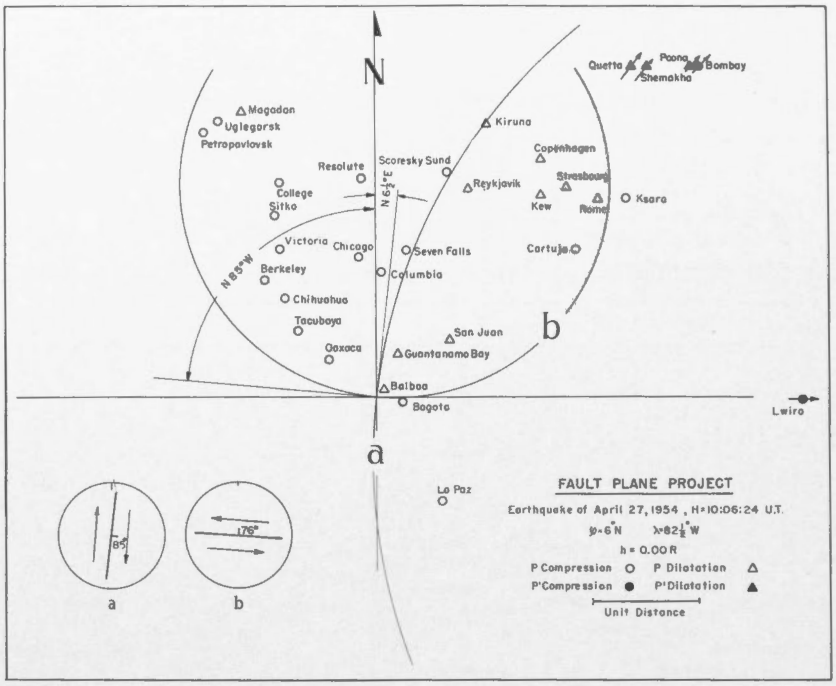

FIGURE 6.

Earthquakes of 10:49:27 and 11:34:34, April 29, 1954. ø = 28½°N, λ = 113°W

These two earthquakes had the same epicentre, and their mechanisms were so nearly identical that a single solution suffices for the two. This is shown in Figure 7, the data plotted being those for the main shock. It will be noted that a good separation is obtained in California, between Berkeley and Mount Hamilton, and again in Mexico. There is however a good deal of confusion in Europe, and this has resulted in a high number of inconsistencies in the P observations. We have drawn circle *b* in a mean position; if we had drawn it smaller we might have made Rathfarnham correct, but at the expense of Tacubaya and Puebla. If we had made circle *b* larger the European dilatations could have been correct at the expense of the European compressions. Since most of the dilatations were called doubtful, and most of the compressions were not qualified the present solution seems the best compromise. We must admit an uncertainty in the dip of plane *b* of about ±4°.

The score for the foreshock is given in Table IX and that for the main shock in Table X.

TABLE IX

	Direct Phases			Reflected Phases				Grand Total
	P	P_1'	Total	PP	PPP	PcP	Total	
Total Number of Observations...........	40	3	43	9	1	1	11	54
Number of Inconsistent Observations......	10	0	10	4	1	0	5	15

TABLE X

	Direct Phases			Reflected Phases				Grand Total
	P	P_1'	Total	PP	PPP	PcP	Total	
Total Number of Observations............	40	6	46	9	1	4	14	60
Number of Inconsistent Observations......	9	0	9	4	1	2	7	16

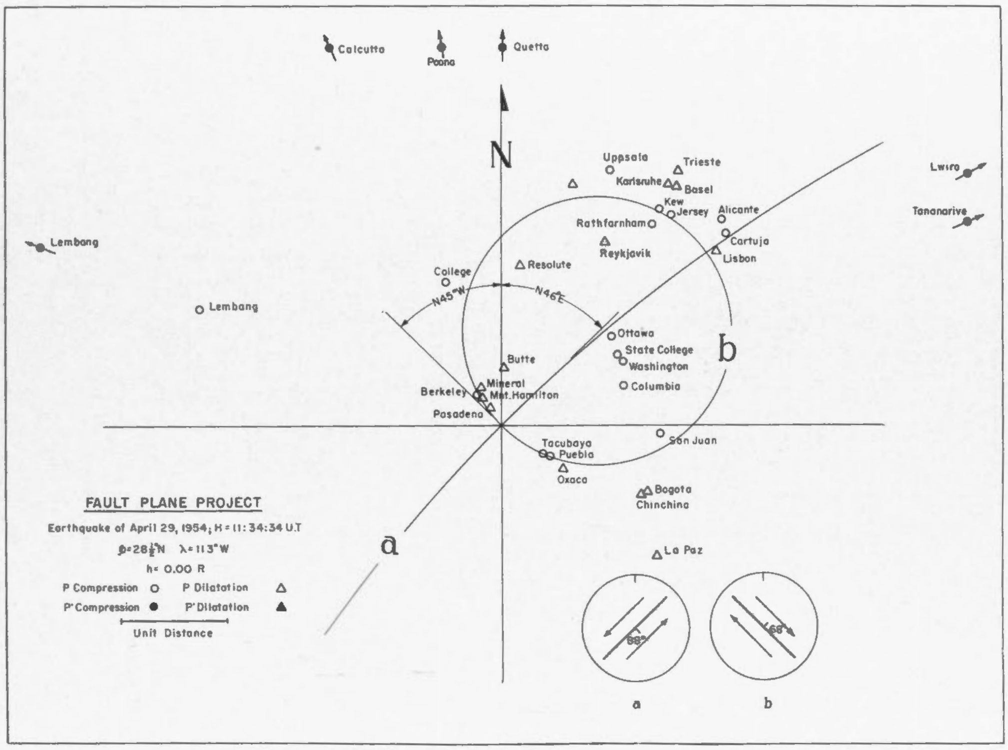

FIGURE 7.

Earthquake of 13:02:37, April 30, 1954. $\phi = 39°N$, $\lambda = 22°E$

The solution for this earthquake, shown in Figure 8, is a very satisfactory one, although the exact position of circle *a* may be questioned. As shown in Table XI, the

TABLE XI

	Direct Phases			Reflected Phases				Grand Total
	P	P_1'	Total	PP	pP	PPP	Total	
Total Number of Observations............	76	4	80	15	1	6	22	102
Number of Inconsistent Observations......	10	3	13	9	0	3	12	25

score for the P phases is satisfactory, and although the P′ phases have a very poor score, most of these observations were described as doubtful by our collaborators. We might have made circle *b* smaller, to make San Juan inconsistent and Lwiro consistent; however the San Juan observation was described as an *i* while the direction observed at Lwiro was described as doubtful.

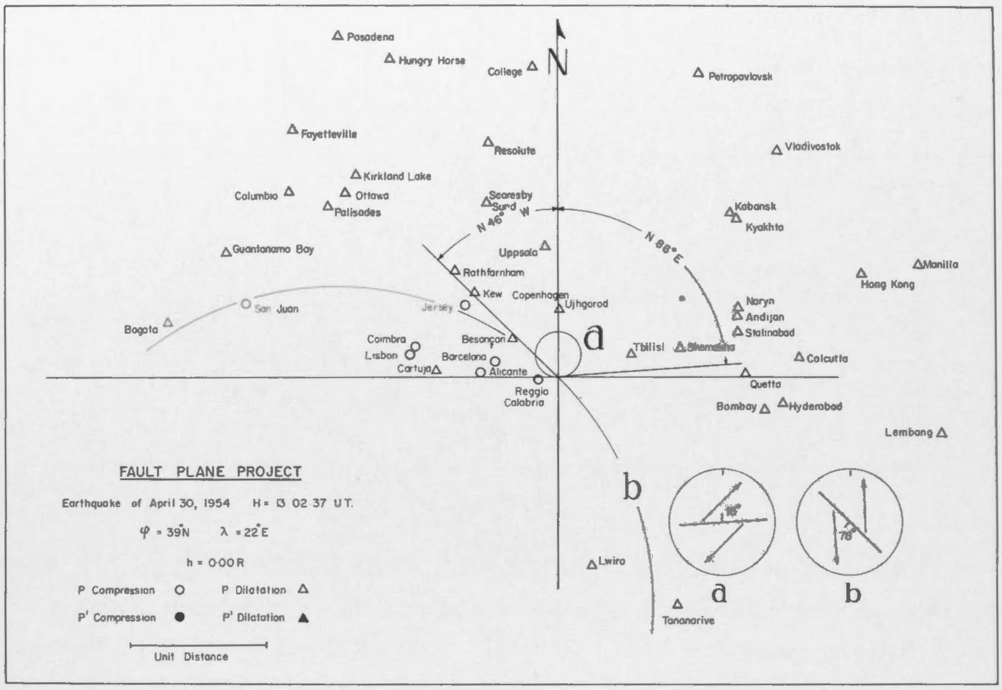

FIGURE 8.

The position of circle *a* appears to be very closely defined by the data but we must remember that the extended distances for short epicentral distance are not too reliable, so that the smaller circle may not be as closely defined as it appears to be. There seems little doubt however that the faulting is approximately normal.

Earthquake of 15:29:40, May 3, 1954. $\phi = 51\frac{1}{2}°N, \lambda = 159\frac{1}{2}°E$

The solution for this earthquake is shown in Figure 9, and the score is given in Table XII. The solution is straightforward except for some difficulties in Europe. A number of Italian stations (only Rome is shown in the diagram) recorded compressions. These

TABLE XII

	Direct Phases		Reflected Phases					Grand Total
	P	Total	PP	pP	PPP	PcP	Total	
Total Number of Observations............	74	74	6	1	2	4	13	87
Number of Inconsistent Observations......	11	11	3	0	0	3	6	17

could have been made consistent by increasing the radius of circle *b* slightly, but this would have made a number of other stations inconsistent, as shown in the figure. The present solution is a compromise which cannot be very far from correct.

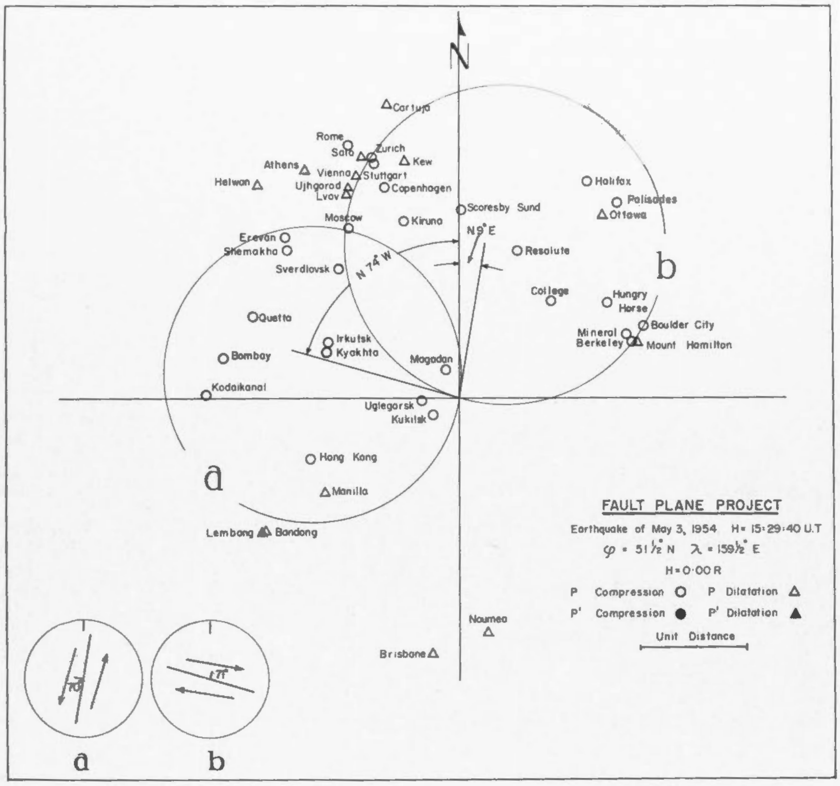

FIGURE 9.

Earthquake of 22:39:26, May 14, 1954. $\phi = 36°N, \lambda = 137°E$

The solution for this earthquake is shown in Figure 10 and the score is given in Table XIII. The solution is quite straightforward, and the number of inconsistencies in the direct observations is gratifyingly small.

TABLE XIII

	Direct Phases			Reflected Phases						Grand Total
	P	P'ᵢ	Total	PP	pP	pPP	PPP	PcP	Total	
Total Number of Observations....	91	3	94	14	16	2	2	3	37	131
Number of Inconsistent Observations..................	10	0	10	7	7	0	0	2	16	26

Earthquake of 08:04:42, July 6, 1954. $\phi = 46\frac{1}{2}°N, \lambda = 153\frac{1}{2}°E$

We have not been able to obtain a unique solution for this earthquake; to illustrate the difficulty all the stations have been plotted on the diagram, although only a few of

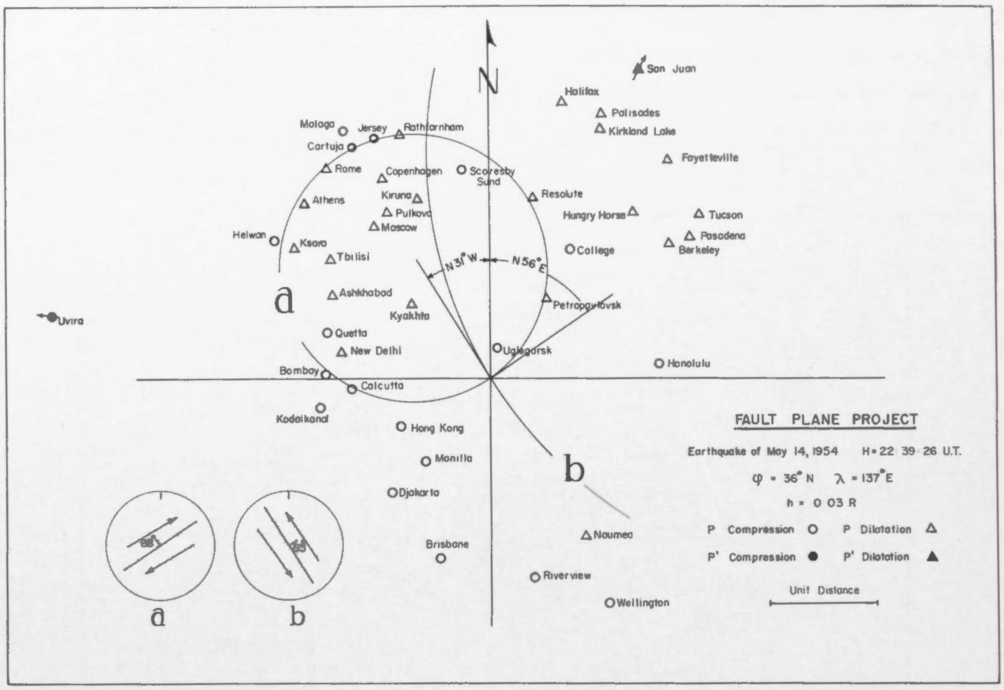

FIGURE 10.

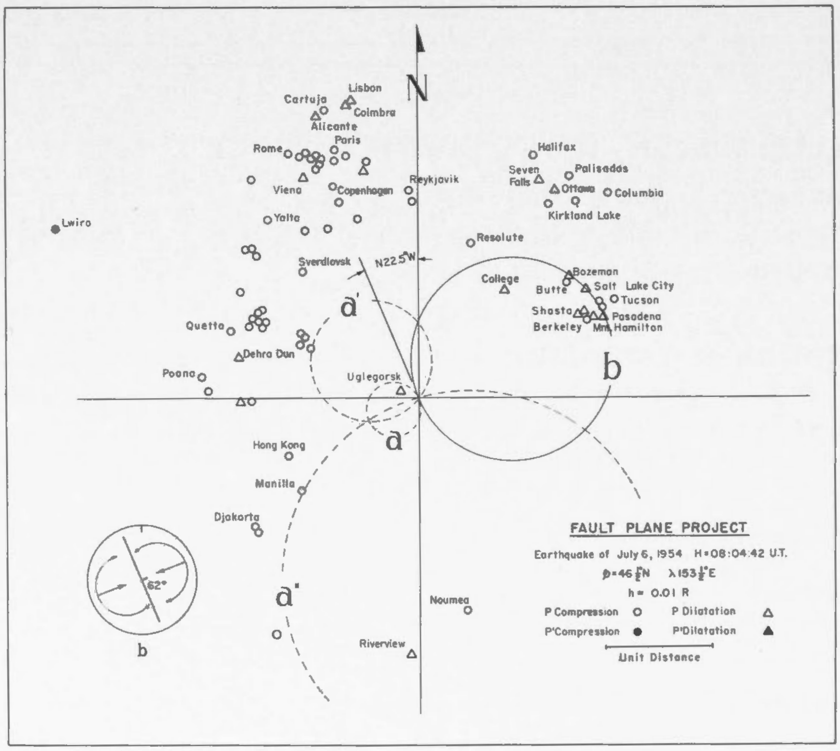

FIGURE 11.

them have been identified. As shown in Figure 11, circle *b* is well defined, but circle *a* may vary through wide limits. It has been shown in its extreme positions, and also in that position which would give pure thrust faulting. The insert diagram shows that anything between pure thrust faulting and almost pure strike-slip faulting would be consistent with the data. The score of the solution is given in Table XIV.

TABLE XIV

	Direct Phases			Reflected Phases			Grand Total
	P	P_1'	Total	PP	pP	Total	
Total Number of Observations	77	1	78	10	3	13	91
Number of Inconsistent Observations	12	0	12	3	1	4	16

Earthquake of 04:42:20, August 18, 1954. $\phi = 21\frac{1}{2}°S, \lambda = 176°W$

The solution, shown in Figure 12, is straightforward. The number of observations, and the number of these inconsistent, is shown in Table XV.

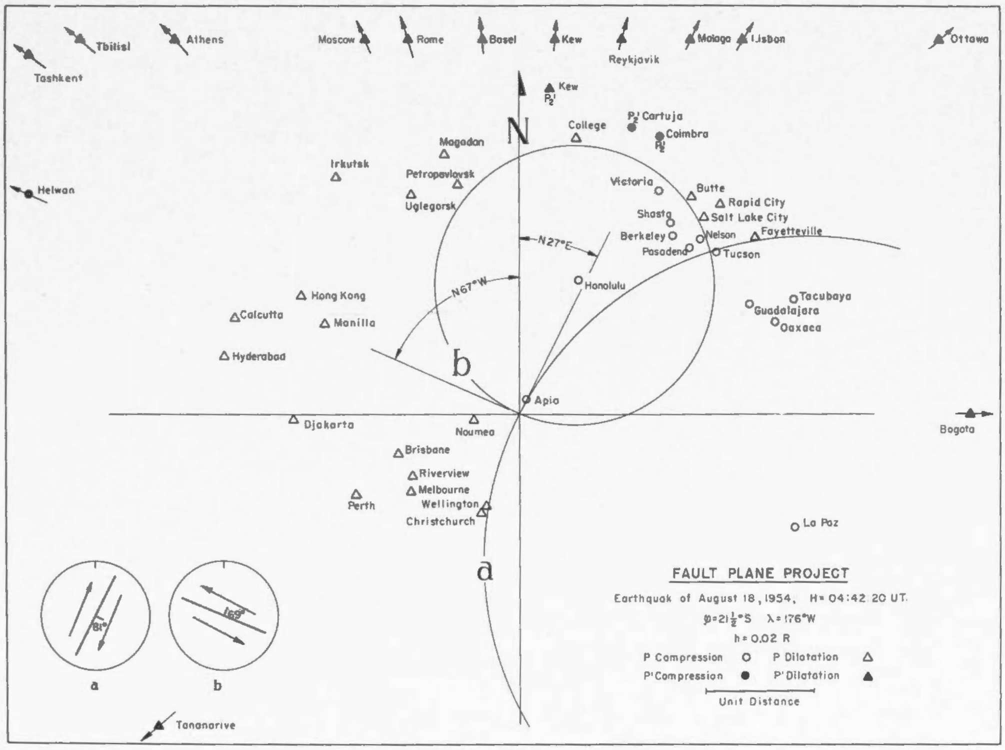

FIGURE 12.

Earthquake of 02:09:55, Sept. 13, 1954. $\phi = 21°S, \lambda = 175\frac{1}{2}°W$

There is some doubt about the proper position for circle *b*. As drawn (*see* Figure 13) it makes Tucson, Bozeman and Palisades correct, the Mexican stations, Swan Island,

TABLE XV

	Direct Phases				Reflected Phases							Grand Total
	P	P'_1	P'_2	Total	PP	PPP	pP	pP'_1	pPP	PcP	Total	
Total Number of Observations..	49	38	3	90	23	2	12	6	3	1	47	137
Number of Inconsistent Observations................	2	9	2	13	11	2	4	0	2	1	20	33

Fayetteville and a large number of reflected phases inconsistent. A better score would be obtained by drawing a larger circle. This has not been done because most of the dilatations have been called doubtful observations whereas most of the compressions have been called certain. In any event the difference would be very slight geologically.

The score is given in Table XVI.

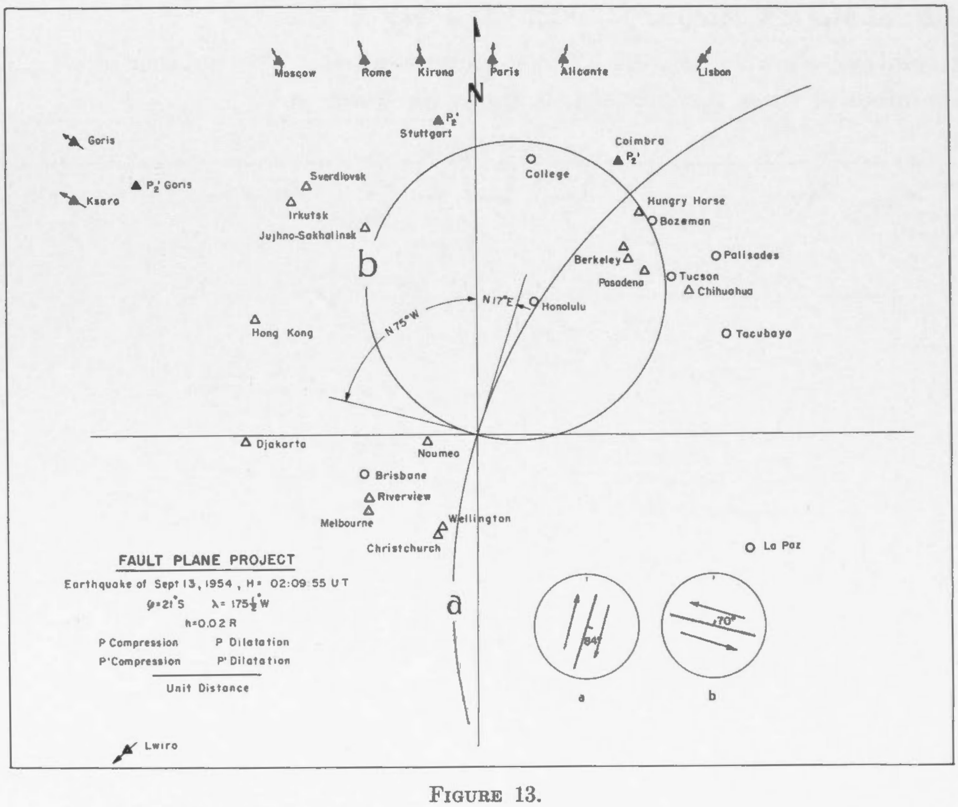

FIGURE 13.

Earthquake of 17:56:08, Sept. 15, 1954. $\phi = 18°S, \lambda = 178\frac{1}{2}°W$

As shown in Table XVII, there is a rather high percentage of inconsistencies among the PKP observations in this solution, but these inconsistent observations are so spread among consistent ones that no separation can be made, and they do not contribute a source of much doubt. There is some doubt about the exact position of circle *b* (*see* Figure 14); Tacubaya might have been made correct at the expense of Victoria. However the difference is slight.

TABLE XVI

	Direct Phases				Reflected Phases							Grand Total
	P	P_1'	P_2'	Total	PP	PPP	pP	pPP	pP_1'	pP_2'	Total	
Total Number of Observations..	35	33	3	71	25	3	7	3	8	1	47	118
Number of Inconsistent Observations................	5	5	1	11	9	2	4	2	4	1	22	33

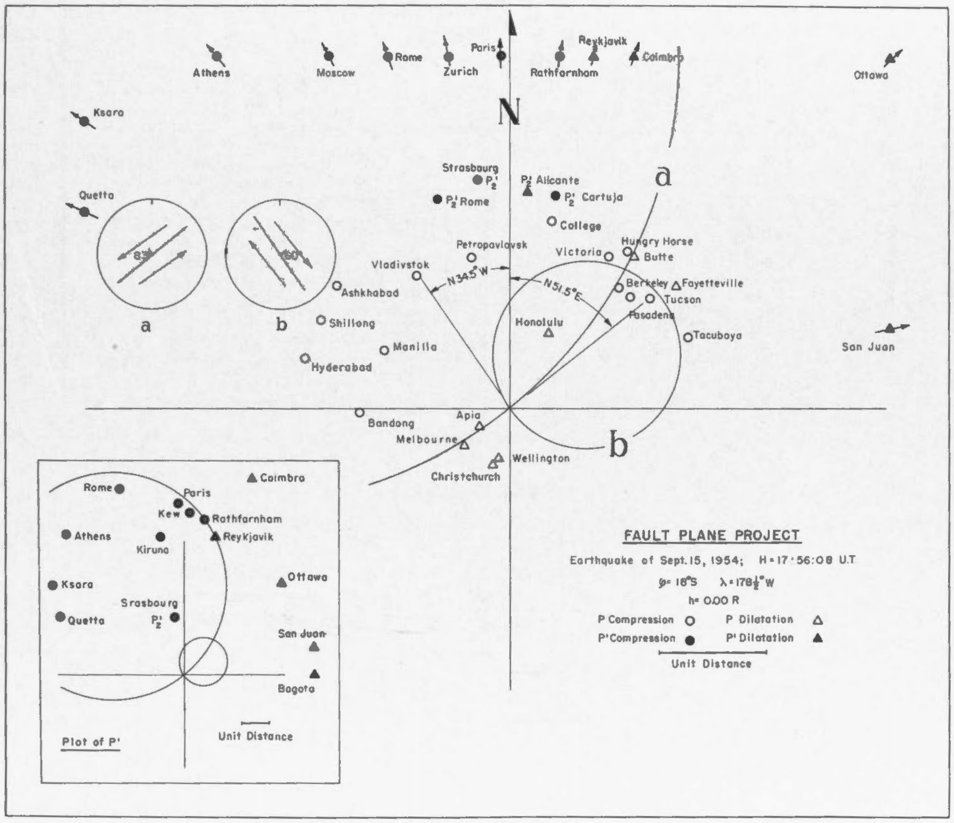

FIGURE 14.

TABLE XVII

	Direct Phases				Reflected Phases							Grand Total
	P	P_1'	P_2'	Total	PP	PPP	pP	pPP	pP_1'	PcP	Total	
Total Number of Observations..	34	41	7	82	13	2	4	1	3	2	25	107
Number of Inconsistent Observations................	4	10	3	17	6	1	2	1	1	1	12	29

Earthquake of 11:18:46, Oct. 3, 1954. $\phi = 60\frac{1}{2}°N$, $\lambda = 151°W$

The solution, shown in Figure 15, is perfectly straightforward, and the number of inconsistent observations shown in Table XVIII is about normal; note however the surprisingly good score of the pP and PPP phases and the very bad score for the PP.

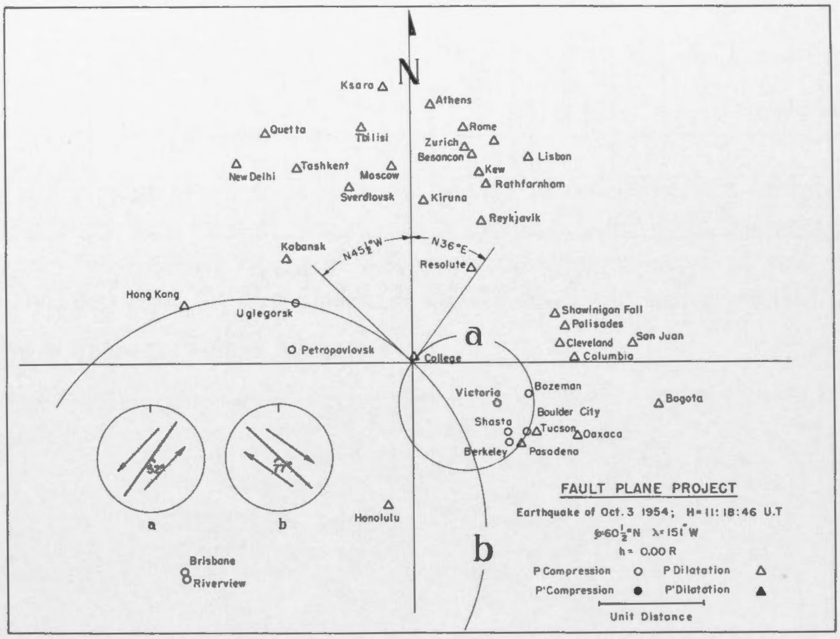

FIGURE 15.

TABLE XVIII

	Direct Phases			Reflected Phases						Grand Total
	P	P_1'	Total	PP	PPP	pP	pPP	PcP	Total	
Total Number of Observations....	90	1	91	15	6	9	3	2	35	126
Number of Inconsistent Observations..................	14	1	15	11	0	1	1	1	14	29

Earthquake of 17:48:35, Jan. 5, 1955. $\phi = 16°S$, $\lambda = 167\frac{1}{2}°E$

As shown in Table XIX, there are fewer observations than usual in this solution, but the percentage of inconsistencies is about normal. The solution is shown in Figure 16.

TABLE XIX

	Direct Phases				Reflected Phases					Grand Total
	P	P_1'	P_2'	Total	PP	PPP	pP	PcP	Total	
Total Number of Observations....	26	21	2	49	12	1	2	1	16	65
Number of Inconsistent Observations..................	4	2	0	6	6	0	2	1	9	15

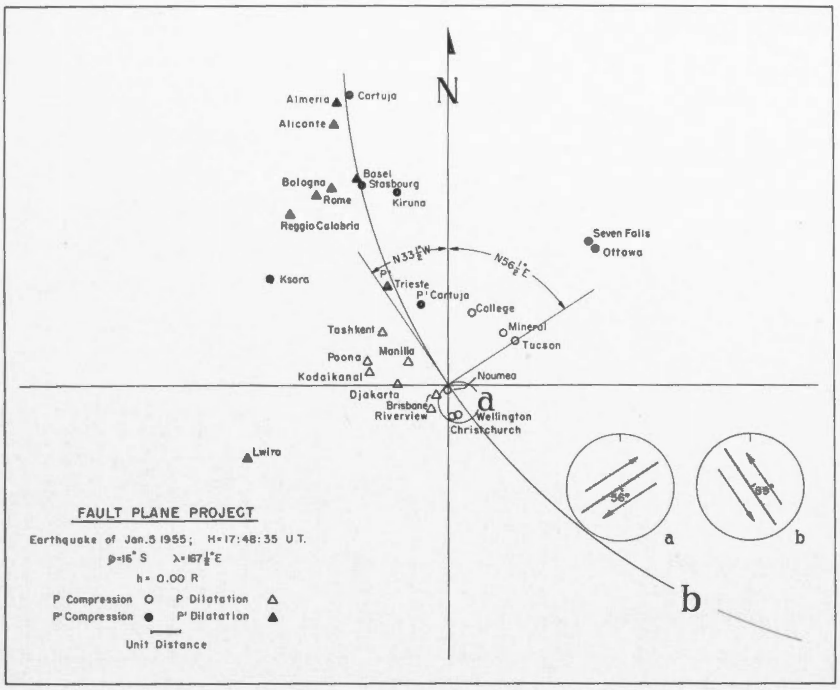

FIGURE 16.

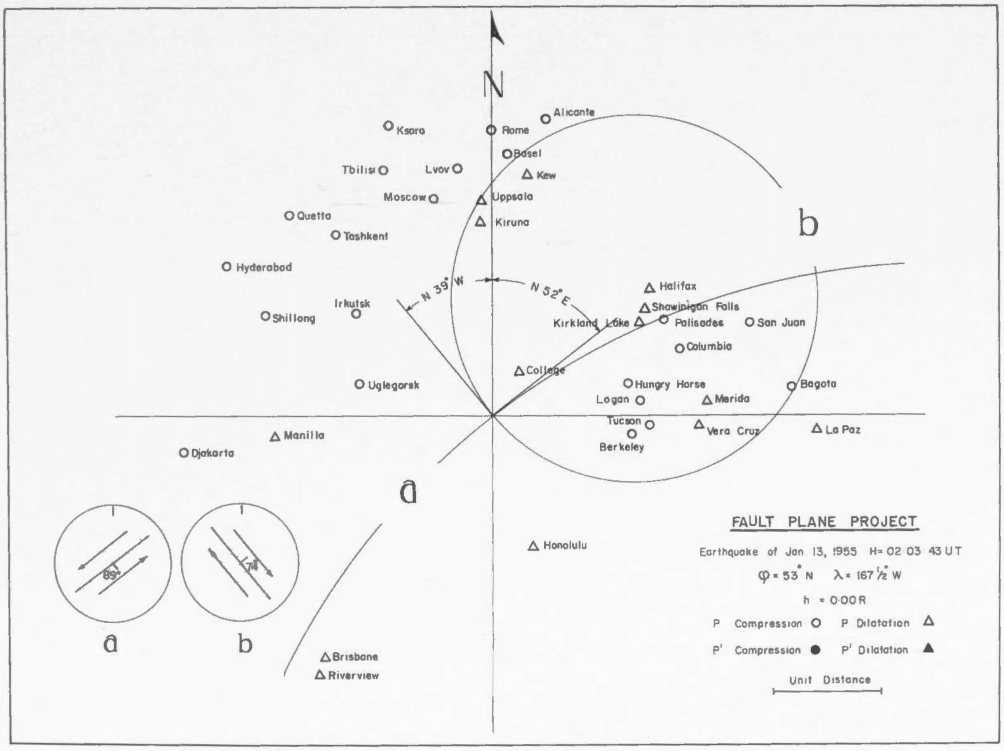

FIGURE 17.

Earthquake of 02:03:43, Jan. 13, 1955. $\phi = 53°N, \lambda = 167\frac{1}{2}°W$

The solution for this earthquake, shown in Figure 17, should be approximately correct, but there is some doubt about the exact position of circle *b*. As drawn it makes the Mexican stations inconsistent, and the stations at San Juan and Bogota consistent. If the circle were to be reduced in radius to reverse this, it would make Kiruna, Uppsala and Kew inconsistent. However something might be accomplished by swinging the circle around, and the fact that a number of Italian stations reported doubtful dilatations (not shown) might support this. There would be no geological significance in the change. The inconsistencies in Italy and Mexico contribute most of those shown in Table XX.

TABLE XX

	Direct Phases			Reflected Phases					Grand Total
	P	P_1'	Total	PP	pP	PPP	PcP	Total	
Total Number of Observations..........	77	1	78	12	2	4	5	23	101
Number of Inconsistent Observations.....	14	1	15	6	1	1	2	9	25

Earthquake of 13:12:04, March 14, 1955. $\phi = 52\frac{1}{2}°N, \lambda = 173\frac{1}{2}°W$

The solution is shown in Figure 18 and the score is given in Table XXI. The solution requires no comment.

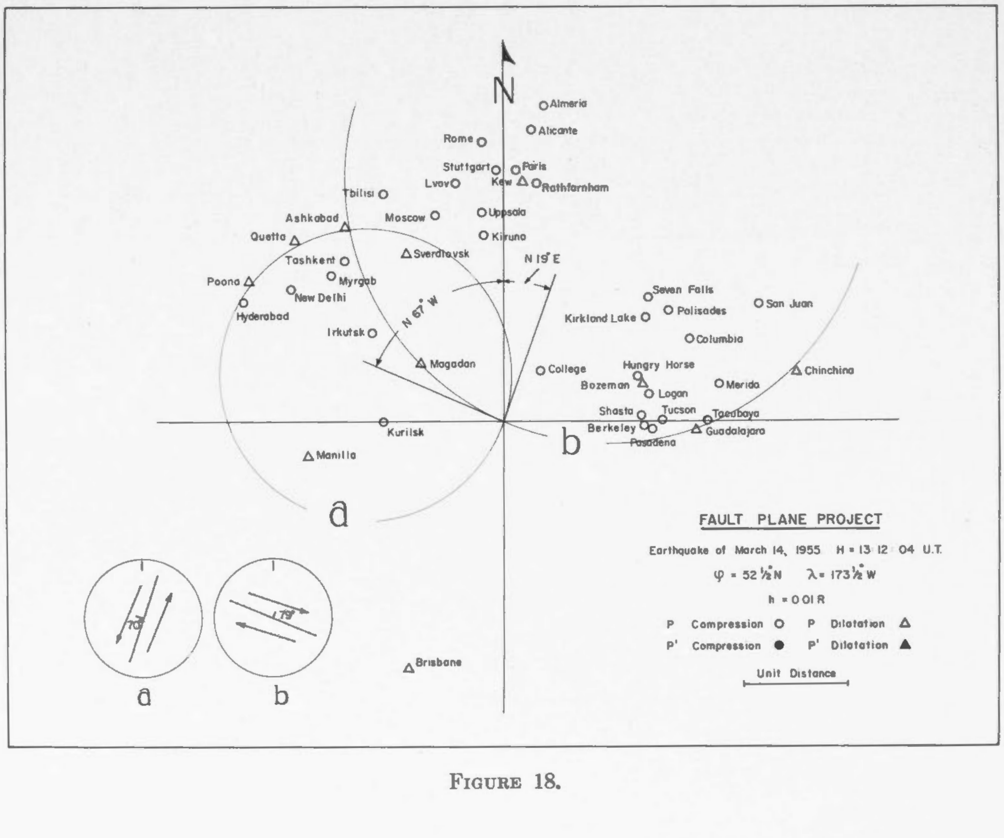

FIGURE 18.

TABLE XXI

	Direct Phases			Reflected Phases						Grand Total
	P	P_1'	Total	PP	PPP	pP	pPP	PcP	Total	
Total Number of Observations....	71	2	73	4	1	15	1	2	23	95
Number of Inconsistent Observations..................	12	1	13	1	1	7	1	0	10	23

Earthquake of 18:35:27, April 17, 1955. $\phi = 52°N$, $\lambda = 159\frac{1}{4}°E$

In the solution, shown in Figure 19, the position of circle *a* is clear, but circle *b* cannot be fixed exactly. As drawn, it makes Kiruna, Uppsala, Copenhagen and Paris correct,

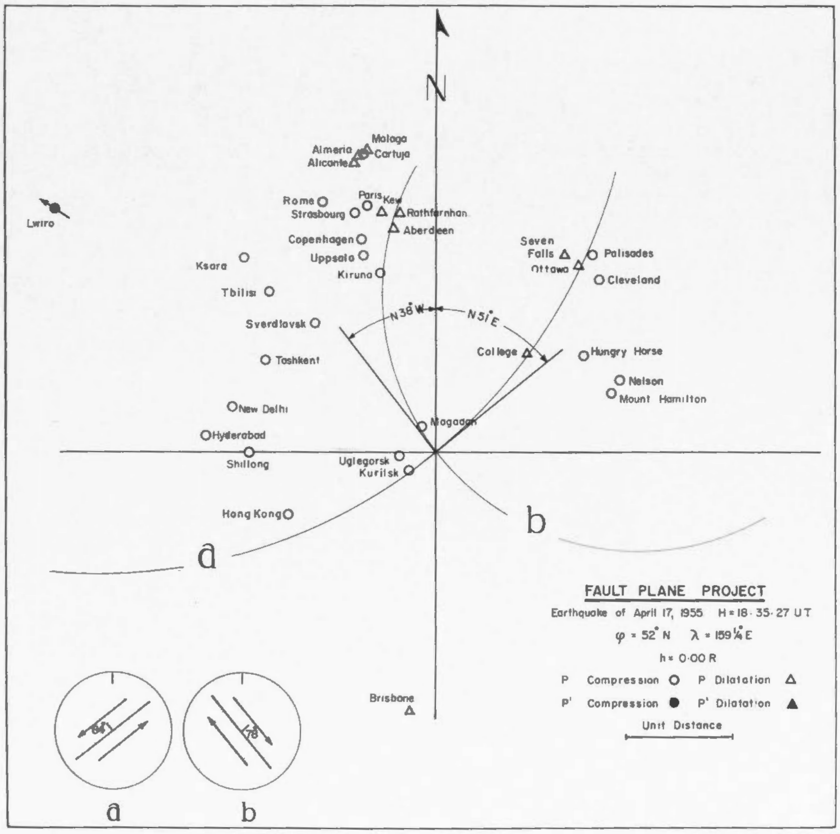

FIGURE 19.

Kew, Alicante, Almeria and Malaga inconsistent. These could have been reversed by increasing the radius of the circle to correspond to a dip of 82°; the difference is of no geological consequence, but the uncertainty is reflected in the high percentage of errors in the P observations, as shown in Table XXII.

TABLE XXII

	Direct Phases			Reflected Phases				Grand Total
	P	P_1'	Total	PP	pP	PcP	Total	
Total Number of Observations............	56	2	58	3	2	3	8	66
Number of Inconsistent Observations......	13	0	13	0	1	1	2	15

Earthquake of 20:24:05, April 19, 1955. $\phi = 30°S$, $\lambda = 72°W$

There are relatively few data for this earthquake, but the solution shown in F gure 20 accounts for these so well that publication seems justified. The percentage of inconsistent observations in the directest phases is gratifyingly low, as shown in Table XXIII.

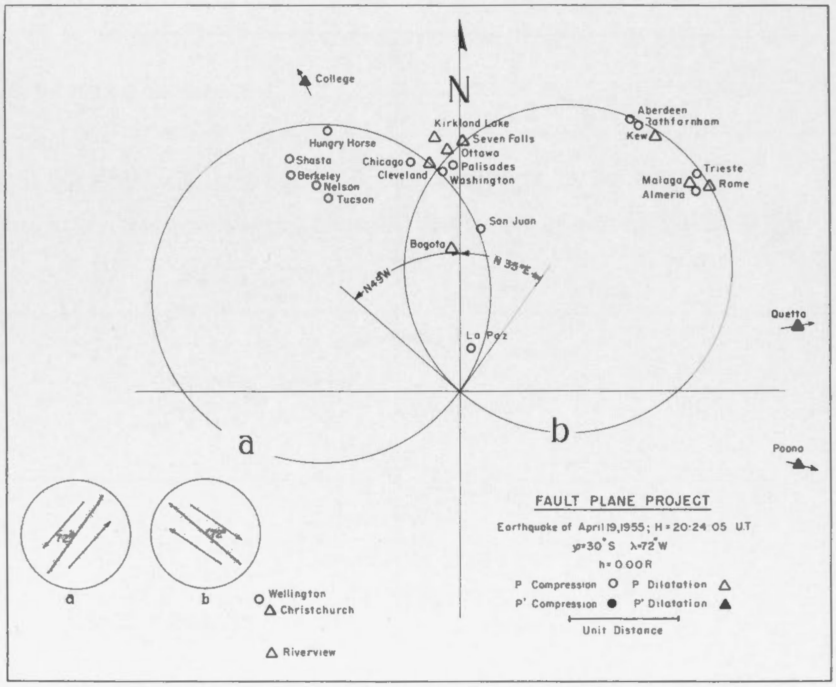

FIGURE 20.

TABLE XXIII

	Direct Phases			Reflected Phases			Grand Total
	P	P_1'	Total	PP	PPP	Total	
Total Number of Observations...............	34	5	39	13	3	16	55
Number of Inconsistent Observations.........	4	1	5	8	1	9	14

Earthquake of 12:31:41, May 30, 1955. $\phi = 24\frac{1}{2}°N, \lambda = 142\frac{1}{2}°E$

There were so many inconsistent observations in the direct phases in this solution (*see* Figure 21 and Table XXIV) that we seriously considered withholding its publication, particularly since many of these inconsistent observations came from stations which are normally dependable. However most of these observations were surrounded by consistent ones so that the solution has a reasonable degree of probability.

The very high percentage of inconsistencies in pP is worthy of note.

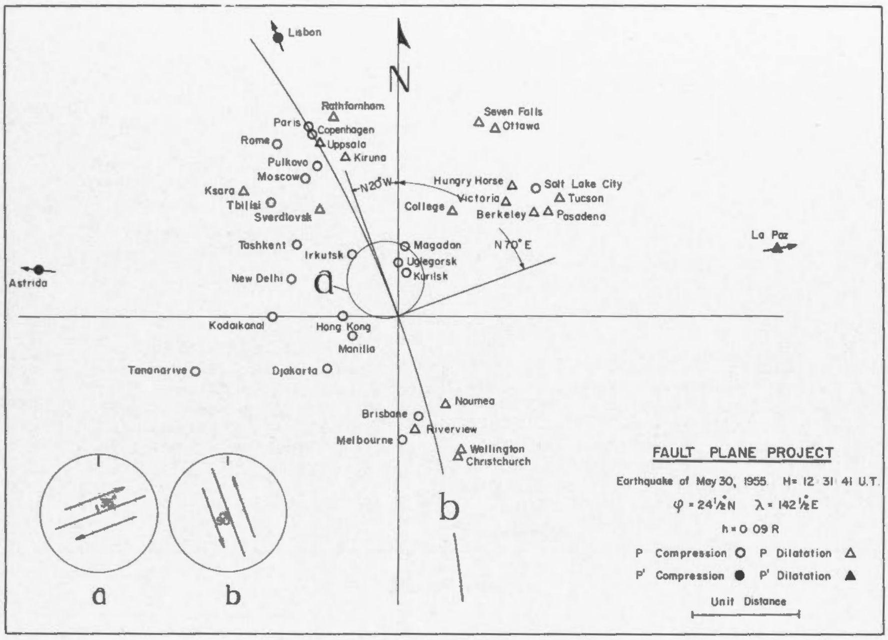

FIGURE 21.

TABLE XXIV

	Direct Phases			Reflected Phases						Grand Total
	P	P_1'	Total	PP	PPP	pP	pPP	PcP	Total	
Total Number of Observations....	88	3	91	22	5	26	5	2	60	151
Number of Inconsistant Observations..................	19	1	20	8	2	18	1	2	31	51

Earthquake of 00:18:56, June 2, 1955. $\phi = 51\frac{1}{2}°N \ \lambda = 180°$

In this earthquake, which occurs at the junction of the two sections of the Aleutian arc, a line striking N86°E separates most of the compressions, lying to the north, from most of the dilatations, lying to the south. To show how well this has been accomplished all the points have been drawn in Figure 22 although only some of them have been identified. As drawn, the line passes through Hong Kong, Kurilsk, Berkeley and Mount Hamilton, and they may be regarded as correct. The only serious problem arises in the stations of western North America. Six of the stations—Hungry Horse, Victoria, Shasta, Boulder City, Tucson and Woody—recorded compressions, eight of them—Butte, Bozeman, Salt Lake City, Mineral, Nelson, Berkeley and Mount Hamilton—recorded

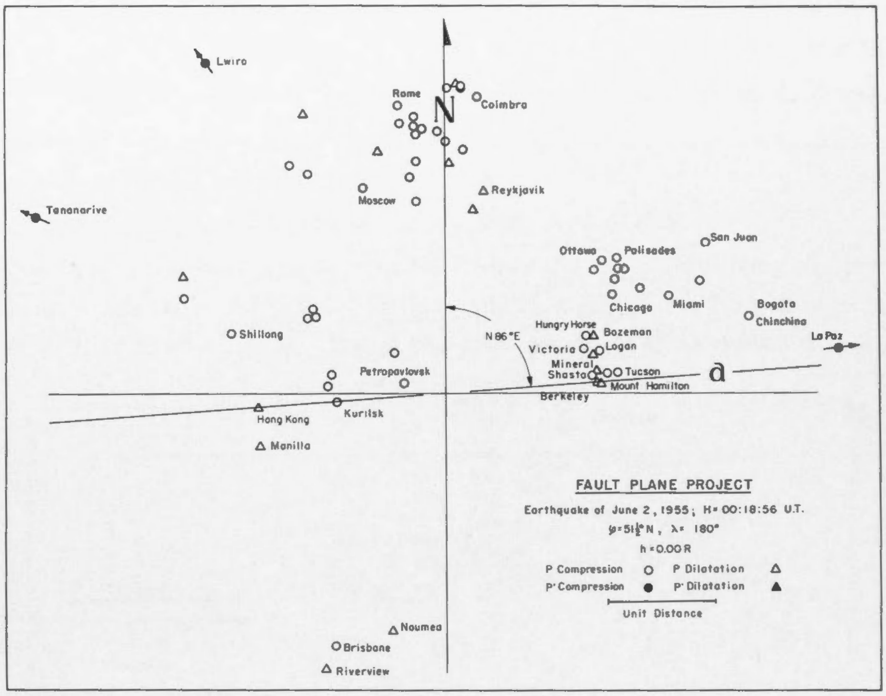

FIGURE 22.

dilatations. If no second circle is drawn through the area the six compressions and the dilatations at Berkeley and Mount Hamilton are consistent, against six inconsistent dilatations. If we draw a circle to include the dilatations at Bozeman and Nelson all the dilatations become consistent but all the compressions inconsistent. Clearly there is no statistical justification for drawing a second circle through the area. Hence the second circle could be any small circle drawn on the line *a* as centre—in particular the circle of zero radius drawn at the centre and representing a horizontal plane through the focus would be justified. In any case the direction of the null vector, but not its dip, is known. The data are summarized in Table XXV.

TABLE XXV

	Direct Phases			Reflected Phases						Grand Total
	P	P_1'	Total	PP	PPP	pP	pPP	PcP	Total	
Total Number of Observations....	78	3	81	6	2	1	1	4	14	95
Number of Inconsistent Observations..................	16	0	16	4	0	0	1	2	7	23

Earthquake of 12:07:25 June 20, 1955. $\phi = 51\frac{1}{2}°N$, $\lambda = 180°$

This earthquake has the same epicentre as that just discussed, but the solution, shown in Figure 23 is completely different. The percentage of inconsistent direct observations is again rather high, and it seems probable that both these solutions should be accepted

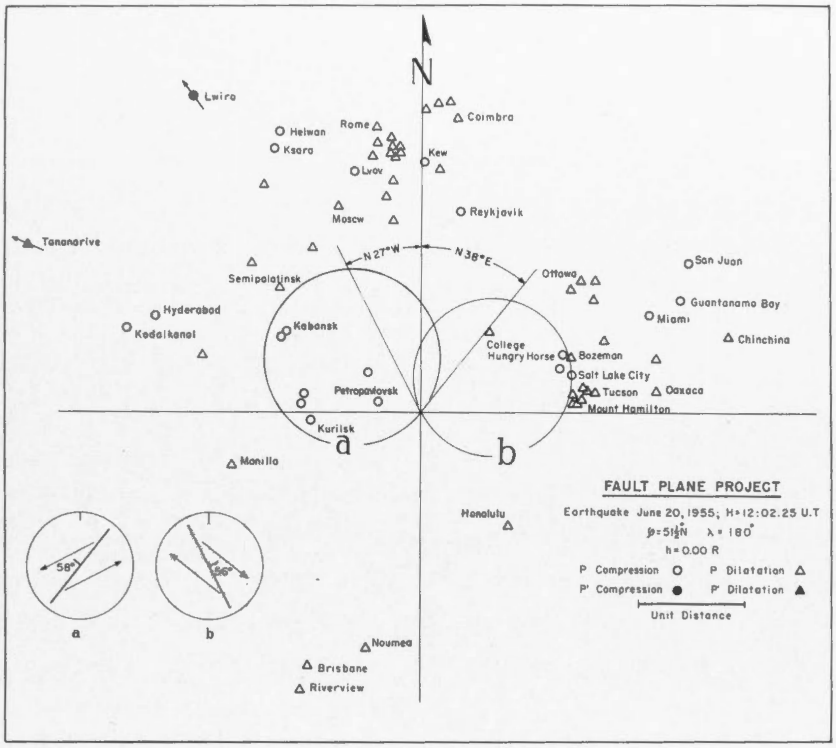

FIGURE 23.

with reservations. Most of the inconsistent observations derive from compressional observations at the greater distances, such for example as San Juan, Lwiro, Kodaikanal and the like. These are persistent enough to suggest the possibility of another mechanism. The score is given in Table XXVI.

TABLE XXVI

	Direct Phases				Reflected Phases						Grand Total
	P	P_1'	P_2'	Total	PP	PPP	pP	PcP	pPPP	Total	
Total Number of Observations....	71	2	1	74	10	4	7	6	1	28	102
Number of Inconsistent Observations..................	16	1	1	18	5	2	4	4	0	15	33

Earthquake of 07:07:08, July 16, 1955. $\phi = 37\frac{1}{2}°N$, $\lambda = 27°E$

The solution is shown in Figure 24. Circle *b* is extremely well defined by the separation in Europe and in the western United States, but circle *a* is not so well limited. It might, for example, be made larger to make Sverdlovsk correct and Magadan incorrect, or it might be made much smaller. The score is given in Table XXVII.

TABLE XXVII

	Direct Phases			Reflected Phases				Grand Total
	P	P_1'	Total	PP	PPP	PcP	Total	
Total Number of Observations............	71	2	73	12	3	1	16	89
Number of Inconsistent Observations......	14	2	16	6	1	0	7	23

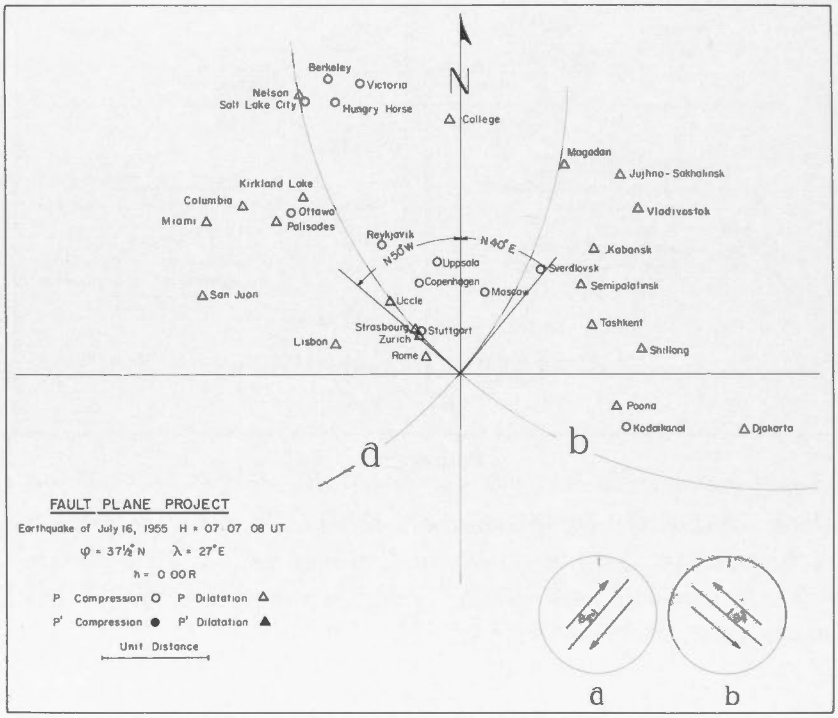

FIGURE 24.

SUMMARY

It was mentioned in the Introduction that this is the first in a second series of papers giving fault plane solutions. Until more solutions have been completed in this new series there is little to add to the discussion given in the recent paper (Hodgson, 1957) which reviewed the solutions of the first series. For that reason we simply provide the summary shown in Table XXVIII; the form of this table and the order in which the material is arranged is the same as that used in the review paper.

Throughout the present paper the solutions have been based on P and PKP alone, and the reflected phases have been tested for accuracy with reference to these solutions. The score for the reflected phases has been given with each solution, but the results for

TABLE XXVIII

EARTHQUAKE				PLANE a					PLANE b					NULL VECTOR		DEXTRAL Solution	SINISTRAL Solution
Date	φ	λ	Focal Depth-km.	Strike Direction	Dip Direction	Dip	Strike Component	Dip Component	Strike Direction	Dip Direction	Dip	Strike Component	Dip Component	Trend	Plunge		
New Zealand - Kermadecs - Tongas - Fiji																	
February 19A, 1954	30°S	177.7°W	Normal	N29.5°E	S60.5°E	87°	.985	+.175	N60°W	N30°E	80°	.999	+.053	N48°E	79.5°	b	a
- Alternative Solution -				N78.5°E	N11.5°W	73°	.889	+.459	N21°W	S69°W	64°	.946	+.325	N72°W	58°	b	a
August 18, 1954	21.5°S	176°W	150	N27°E	S63°E	81°	.932	-.363	N67°W	N23°E	69°	.986	-.168	N50°E	66.8°	a	b
September 13, 1954	21°S	175.5°W	150	N17°E	S73°E	84°	.939	-.345	N75°W	N15°E	70°	.994	-.112	N32°E	69.6°	a	b
September 15, 1954	18°S	178.5°W	600	N51.5°E	N38.5°W	83°	.864	-.504	N34.5°W	N55.5°E	60°	.990	-.141	N39.5°E	59.4°	b	a
New Hebrides																	
January 5A, 1955	16°S	167.5°E	Normal	N56.5°E	S33.5°E	56°	.999	-.022	N33.5°W	N56.5°E	89°	.820	-.572	S35.5°E	55.9°	a	b
Bonins - Japan - Sakhalins - Kuriles - Kamchatka																	
May 30, 1955	24.5°N	142.5°E	600	N70°E	N20°W	35°	1.000	-.000	N20°W	S70°W	90°	.574	-.819	N21°W	35.4°	a	b
May 14, 1954	36°N	137°E	250	N56°E	N34°W	68°	.991	+.132	N31°W	N59°E	83°	.926	+.378	N14.5°W	66.9°	a	b
July 6, 1954	46.5°N	153.5°E	100	←	Not defined			+ →	N22.5°W	N67.5°E	62°	←	+		Not defined		→
May 3, 1954	51.5°N	159.5°E	Normal	N9°E	N81°W	70°	.938	-.346	N74°W	N16°E	71°	.932	-.362	N34°W	62.2°	b	a
April 17, 1955	52°N	159.2°E	Normal	N51°E	N39°W	84°	.978	-.210	N38°W	N52°E	78°	.994	-.107	N25°E	76.9°	b	a
Aleutians - Alaska																	
June 2, 1955	51.5°N	180°	Normal	N86°E	←	90°				Not defined				N86°E			→
June 20, 1955	51.5°N	180°	Normal	N38°E	N52°W	58°	.752	-.660	N27°W	N63°E	56°	.769	-.639	N7.5°E	39.7°	b	a
April 17, 1954	51.5°N	179°W	Normal	N87.5°E	N2.5°W	82°	.994	-.106	N3°W	S87°W	84°	.990	-.140	N40°W	80.0°	a	b
- Alternative Solution -				N45°E	S45°E	84°	.965	-.261	N46°W	N44°E	75°	.994	-.108	N66°E	74.3°	a	b
March 14, 1955	52.5°N	173.5°W	100	N19°E	N71°W	70°	.979	-.203	N67°W	N23°E	79°	.938	-.348	N39°W	66.3°	b	a
January 13, 1955	53°N	167.5°W	Normal	N52°E	S38°E	89°	.961	+.275	N39°W	N51°E	74°	.999	+.018	N66°E	73.3°	b	a
October 3, 1954	60.5°N	151°W	100	N36°E	S54°E	52°	.958	-.285	N45.5°W	S44.5°W	77°	.775	-.632	S31°E	49.3°	b	a
Pacific Coast of North America																	
April 29A, 1954	28.5°N	113°W	Normal	N46°E	S44°E	88°	.925	+.379	N45°W	N45°E	68°	.999	+.038	N50°E	68°	b	a
April 29B, 1954	28.5°N	113°W	Normal	N46°E	S44°E	88°	.925	+.379	N45°W	N45°E	68°	.999	+.038	N50°E	68°	b	a
February 19B, 1954	12.5°N	87.5°W	Normal	N28.5°E	N61.5°W	55°	.985	-.170	N55°W	N35°E	82°	.815	-.579	N44°W	53.3°	b	a
South America																	
April 27, 1954	6°N	82.5°W	Normal	N6.5°E	S83.5°E	85°	.970	-.243	N85°W	N5°E	76°	.996	-.090	N27°E	75.2°	a	b
April 19, 1955	30°S	72°W	Normal	N35°E	N55°W	72°	.946	-.325	N49°W	N41°E	72°	.946	-.325	N6°W	64.4°	b	a
Mediterranean																	
July 16, 1955	37.5°N	27°E	Normal	N40°E	N50°W	84°	.995	+.105	N50°W	N40°E	84°	.995	+.105	N5.5°W	81°	a	b
April 30, 1954	39°N	22°E	Normal	N86°E	N4°W	18°	.998	-.069	N46°W	S44°W	78°	.954	-.301	N48.5°W	13°	a	b

TABLE XXIX

	PHASE					
	PP	PPP	pP	pP′	pPP	PcP
Number of Observations	277	58	109	19	21	48
Number of Inconsistencies	128	25	52	6	10	25
Percentage of Inconsistencies	46.2	43.1	47.7	31.6	47.6	52.1

all the solutions are summarized in Table XXIX. This table will be discussed in more detail in another paper (Hodgson and Adams, in press), but it is clear that the reflected phases are producing random observations and should not be used.

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AN INVESTIGATION OF MAGNETIC PULSATIONS AT CANADIAN MAGNETIC OBSERVATORIES

BY

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Erratum

Page 276, line 23, *following* "the theoretical value of the slope" *insert* "is".

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ABSTRACT

More than 1,000 pulsations, with approximately constant periods and ranges exceeding 3 gammas, have been studied using Meanook and Agincourt standard run magnetograms for the years 1951 to 1954. This investigation confirms the existence of two separate classes of pulsations, differing in form, time of diurnal occurrence, and mean period. Some additional characteristics reported earlier from Scandinavia are confirmed, but it is now thought that the narrow band Rolf micropulsations are not infrequent $\sim$ 1200 kms. south of the auroral zone in Canada. Very few regular pulsations were observed on magnetograms from stations north of the auroral zone.

Although magnetohydrodynamic waves in the upper parts of the ionosphere provide a possible periodic explanation, the different times of occurrence of the classes in Scandinavia and Canada, and even across Canada, the relationship of the primary sources of pulsations to magnetic disturbance measured by K-indices, and the southern geomagnetic extension in Canada of observable pulsations remain unexplained. Screening effects in the lower ionosphere are considered and provide one explanation of the observed amplitude-period trend.

INTRODUCTION

Quasi-periodic magnetic field disturbances have been commonly reported since continuous photographic recordings of field components were first made a century ago. Fluctuations occur with periods ranging from a few minutes to a fraction of a second, and with amplitudes from several gammas (one gamma = 10^{-5} oersted) to the lowest detectable limit of the equipment used (nowadays $\sim 10^{-2}$ gammas at 1 c.p.s.). The fluctuations consist of components with widely variable period (wide frequency band disturbance) and, more infrequently, components with a quasi-periodic nature (narrow band disturbance). These latter have been discussed previously by a number of authors notably Birkeland (1901), Rolf (1931), Harang (1936) and Sucksdorff (1939) using the records from European observatories. The nomenclature used is not very precisely defined, but in general regular pulsations are classed as micropulsations when the amplitude of the perturbation does not exceed about 3 gammas, and as giant pulsations or Rolf micropulsations when the amplitude exceeds 3 gammas. The lack of a systematic method of classification and nomenclature makes the character of the reported data very unsatisfactory, and to some extent, confused. Table I is an attempt to summarize the known facts about pulsations in as clear a way as possible. When more than one value for any parameter has been reported, the range of such values is indicated in Table I. It is clear that giant and micropulsations appear to have some quite different properties, in particular their geographical extent being different. From observational evidence, therefore, it is not apparent that they have a common explanation. In Table I two classes of giant pulsations are noted, in the manner first suggested by Sucksdorff (1939). Class A consists of pulsations with an amplitude envelope showing more or less regular modulation, whereas a Class B pulsation has an amplitude remaining approximately constant during much of the time of the pulsation. The two types are thought to exhibit some different properties. The outstanding giant pulsations with a regular shuttle-shaped envelope all naturally appear in Class A.

TABLE I

Summary of Previously Published Characteristics of Magnetic Pulsations

	Micropulsations	Giant Pulsations or Rolf Micropulsations
Duration		20 to 240 mins.
Mean Duration		78-89 mins.
Period	20 to 300 secs.	20 to 300 secs.
Mean period		1.3-2.0 mins.
Range	$<$ 3 gammas	$<$ 30 gammas, $>$ 3 gammas
Classes		A: modulated amplitude B: essentially constant amplitude
Number		A: 10 per year
Diurnal Frequency		A: max. at 3 L.T. B: max. at 10 L.T. } in Scandinavia
Seasonal Distribution	Fairly uniform	Confused—perhaps maximum in equinoxes
Geographical Extent	Perhaps simultaneous over entire earth.	Over limited areas near auroral zone with linear source dimensions ~1000 km.
Field Components		$\Delta Z < \Delta H$ or ΔD, $\Delta Z \sim \frac{1}{2}(\Delta H^2 + \Delta D^2)^{\frac{1}{2}}$
Phase of Components		Not in phase
Solar cycle variation	None	No. at solar min. = twice no. at solar max.: possible different behaviour of classes A, B.

Since all previous descriptions of the transient properties of giant pulsations refer to the European auroral regions, it seemed important to examine the phenomena in Canadian auroral regions. No detailed examination appears to have been made, although Madill and Cook (1956) have examined Meanook magnetograms for the occurrence of a number of short-period phenomena, and Whitham and Loomer (1957) have discussed some of the characteristics of pulsational activity well inside the auroral zone. In particular both the geographical extent of such activity in Canada and the diurnal frequency of occurrence at longitudes nearly 180° away from Scandinavia, were unknown. Of great interest also is the relationship of pulsational activity to magnetic disturbance generally.

It is now thought that magnetohydrodynamic waves are a possible source of giant pulsations, and Lehnert (1956) has shown that the observed periods do correspond to possible modes of oscillation. He suggests that damping is sufficiently small to allow standing waves to exist, and discusses in particular an approximation, in which two modes of oscillation, a longitudinal mode and a transverse (Alfvén) mode, can occur. A standing wave across the auroral zone with induced currents directed along the zone corresponds to the longitudinal mode, whereas a standing wave between ionosphere surfaces corresponds to the transverse case. No detailed discussion of the boundary conditions or the agency exciting an ionosphere resonant frequency appears possible, but Lehnert does suggest that giant pulsations may be limited to the auroral zone because enhancement of electron density caused by auroral discharge can remove the damping, and that the correlation of pulsations with magnetic storminess may be caused partly by an enhancement in conductivity, and partly by an increase in the number and strength of sources which may generate pulsations. Earlier Harang (1939) reported that radio echoes showed pulsations in an ionized region at a height of 650-800 km. with the same period as that of

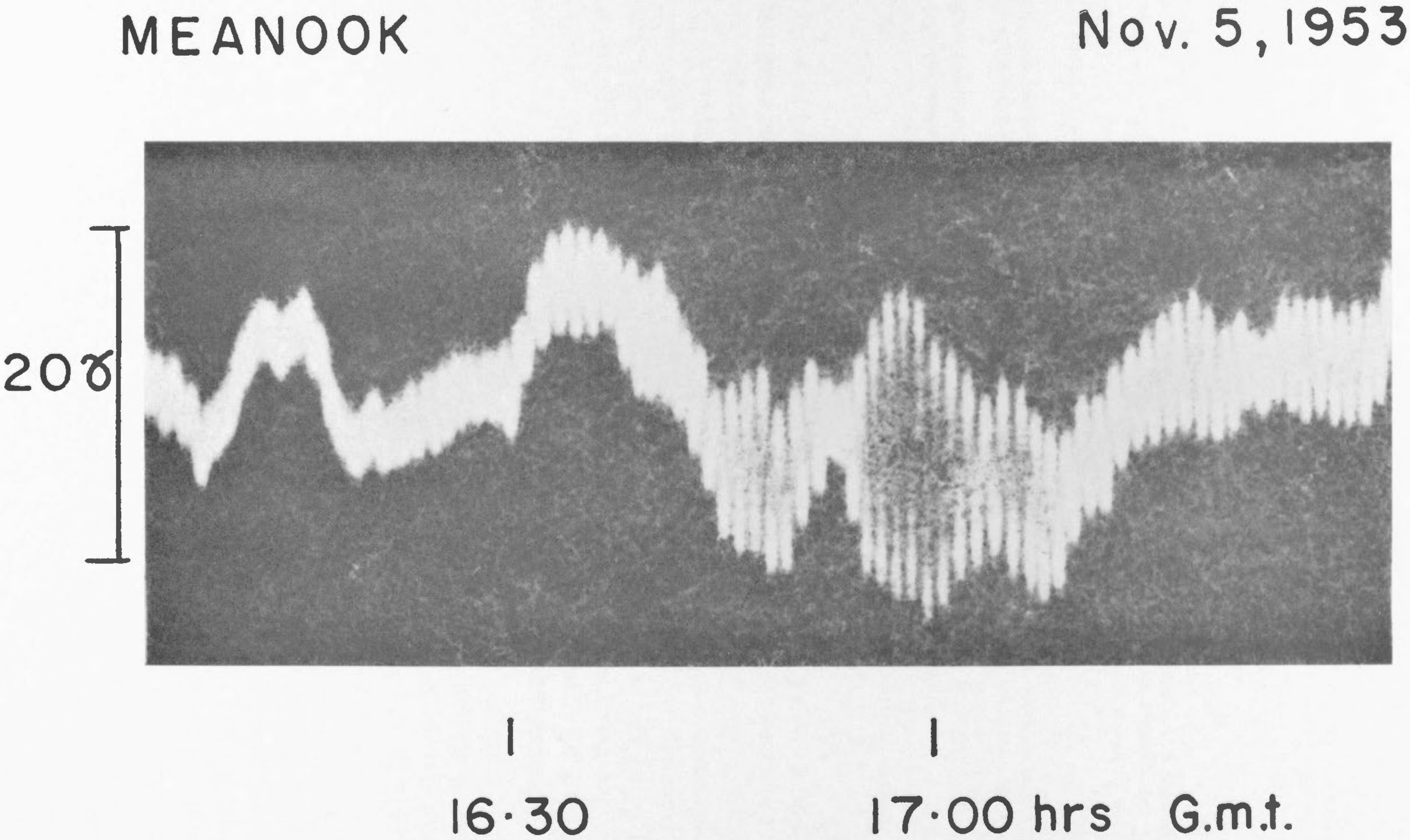

FIGURE 1. Regular pulsation at Meanook in D trace, Nov. 5th, 1953.

a giant pulsation which occurred at the same time. This possibly represents the detection by radio means of a magnetohydrodynamic wave.

The more widespread micropulsations were at first regarded as evidence for the closed periodic orbits calculated by Stormer. The usual objections to Stormer's theory can, of course, be made. Now it seems possible that magnetohydrodynamic phenomena may exist at very great distances from the earth, and the wave-lengths can become very large in interplanetary space.

* Note added in proof.

PROCEDURE

This investigation is limited because no quick run records are available. However, medium to high quality standard-run magnetograms are available. These have paper speeds from 15 to 20 mm. per hour and sensitivities from 2 to 10 gammas per mm. in different field components, depending on the variometers in use. Using these it is possible to investigate many of the properties of the two classes of giant pulsations discussed in Table I. It is of course impossible to measure phase differences between components, or the bandwidth directly, but information on such parameters as the mean period, intensity and duration and the diurnal, and annual frequency of occurrence can be obtained. It is estimated that, in practice, using a hand magnifying glass and good quality magnetograms, any disturbance with a period spread less than 0.3 times the midband period is counted as a regular pulsation. Rather arbitrarily, pulsations of fairly regular period with a maximum range in any field component greater than 3 gammas were examined.

Meanook (geomagnetic latitude, = 61.8°N) observatory records for the years 1951-54, when sufficiently good quality magnetograms for this purpose were available, were first read. Following Meanook, Agincourt (geomagnetic latitude, = 55.0°N) magnetograms for the same time interval were studied, and finally the available magnetograms from Baker Lake (geomagnetic latitude, = 73.7°N) and Resolute (geomagnetic latitude, = 83.0°N) were examined. The geomagnetic latitude of Meanook corresponds most closely to that of the auroral zone station Sodankyla in Finland, whereas Agincourt is generally south of the latitudes for which Rolf pulsations have been reported. The geographical locations of the other Canadian observatories with respect to Meanook are Agincourt ~2700 km. E.S.E., Baker ~1400 km. N.E. and Resolute ~2300 km. N.N.E. The path between Meanook and Baker Lake or Resolute crosses the auroral zone, whereas the path from Meanook to Agincourt lies entirely south of the zone.

Figure 1 is an illustration of a giant pulsation at Meanook obtained by enlarging a portion of the original magnetogram ×5. In an attempt to correlate regular pulsations with magnetic disturbance the A and B classes of pulsations were classified A_d, B_d and A_q, B_q respectively depending upon whether the pulsations appeared during disturbed or quiet magnetic conditions. The assessment of magnetic conditions was, like the magnetic character figure C, entirely subjective. Thus in Figure 1 the pulsation is classified A_q. It is clear that the classification into sub-classes is often an ambiguous process, but

**Since the completion of the work, Committee No. 10 on "Rapid Variations and Telluric Currents" of the International Association of Geomagnetism and Aeronomy, I.U.G.G. has recommended a new system of classification of pulsations. Under this classification, the events described in this paper would in general be listed as pt, and many of them, particularly in the sub-group A, would be listed as pt A. The selection of the outstanding shuttle-shaped regular pulsations described later becomes in the terminology now accepted, the selection of pg.*

was nevertheless believed to be worthwhile. It is convenient to use the term regular pulsations in discussing the results, and reserve the term giant pulsations for very regular shuttle-shaped oscillations only, which are discussed later.

THE RESULTS FROM MEANOOK AND AGINCOURT OBSERVATORIES

In the years 1951-54, 489 regular pulsations were observed at Meanook and 521 at Agincourt. Table II shows the distribution in classes in each of the four years. Allowing for uncertainties introduced (more particularly at Meanook) by the varying definition of the magnetograms, it seems likely—

TABLE II

THE DISTRIBUTION IN CLASSES OF REGULAR PULSATIONS AT MEANOOK AND AGINCOURT DURING 1951-1954

Year	Observatory	A_q	A_d	B_q	B_d	A	B	Total
1951	Meanook...........	5	2	17	5	7	22	29
1952	Meanook...........	5	9	71	16	14	87	101
1953	Meanook...........	14	21	143	16	35	159	194
1954	Meanook...........	26	20	103	16	46	119	165
All	Meanook...........	50	52	334	53	102	387	489
1951	Agincourt..........	11	2	69	12	13	81	94
1952	Agincourt..........	18	1	94	18	19	112	131
1953	Agincourt..........	9	2	82	35	11	117	128
1954	Agincourt..........	22	0	98	48	22	146	168
All	Agincourt..........	60	5	343	113	65	456	521

(1) that the number of pulsations of this type observable at Agincourt ~1200 km. south of the centre of the auroral zone is much the same as the number observed at Meanook ~500 km. south of the centre,

(2) that the number of both the A and B classes increases with decreasing solar activity (1954 was a year of minimum solar activity): the more uniform Agincourt magnetograms suggest about a two to one increase in number from sunspot maximum to sunspot minimum,

(3) that at Meanook about half the A class pulsations occur at magnetically quiet times, whereas about 80 per cent of the B class pulsations occur at quiet times. A similar result for the B class pulsations holds for Agincourt, but an even higher percentage of the A class pulsations appears at quiet times. This suggests that there is no very simple relationship of the two classes to disturbance generally: this must presumably mean that the identification of the B class in particular, is often only possible when the magnetogram records are temporarily quiet.

Figure 2 shows the diurnal frequency distribution for classes A and B, and for the A_q, B_q sub-classes. The ordinate is the number of pulsations occurring in two-hourly intervals of the Greenwich day for the four years. A pulsation is counted in any hourly interval in which it occurs for at least 20 minutes. The times of local noon and midnight are also indicated on the Figure 2 and the typical diurnal variation of the K-index of disturbance is shown. For comparison the results of Sucksdorff (1939) for Sodankyla are shown. It is obvious that the times of maximum of the A and B classes do not agree on a universal time basis or on a local time or local geomagnetic time basis. In particular the nighttime phenomena of Scandinavia become daytime phenomena in Canada and

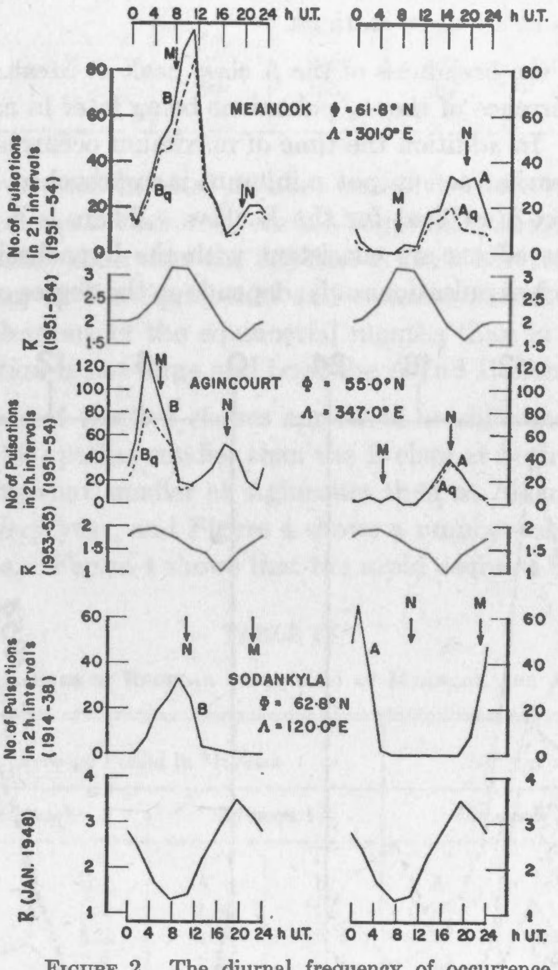

FIGURE 2. The diurnal frequency of occurrence of the A, A_q, B, and B_q classes of regular pulsations and the diurnal variation of the mean K-index at Meanook, Agincourt and Sodankyla.

vice versa. Even across Canada, between Agincourt and Meanook, the only approximate agreement in times is that the broad A class maximum occurs near local noon or local geomagnetic noon at both locations whereas the sharper B class maxima occur at distinctly different times. It is important to consider Agincourt since without these results it would have appeared that there was agreement between Meanook and Sodankyla on local time, but with a reversal of classes. It is of interest to note that the results presented in Figure 2, contrasting the Canadian and Scandinavian data, do not support the idea that the primary sources of pulsational activity approach the earth in a geometrically fixed way, with respect to the sun, and enter the ionosphere along the earth's magnetic field lines.

In Canada the maximum of the B class occurs near the magnetically most disturbed time of the day on the average (slightly after it at Meanook and before it at Agincourt) whereas the broad A class maximum occurs near the magnetically quietest time of day, as indicated in the K-index curves. This variation is the opposite from that found in Scandinavia, and suggests that it is not true that regular pulsations occur shortly after the most disturbed times of day. However, a broad maximum in numbers is related to the minimum K values at all three stations.

It was found that the broadness of the A class peak at Meanook is produced by the time of maximum occurrence of the A_d pulsations being later in each year than the time for the A_q pulsations. In addition the time of maximum occurrence of the total A class becomes increasingly earlier as sunspot minimum is approached. This is illustrated in Figure 3; no such effect is evident for the B class. There is a much smaller effect at Agincourt. Both these effects are consistent with the hypothesis that the diurnal frequency maximum of A class pulsations only, depends on the degree of magnetic disturbance.

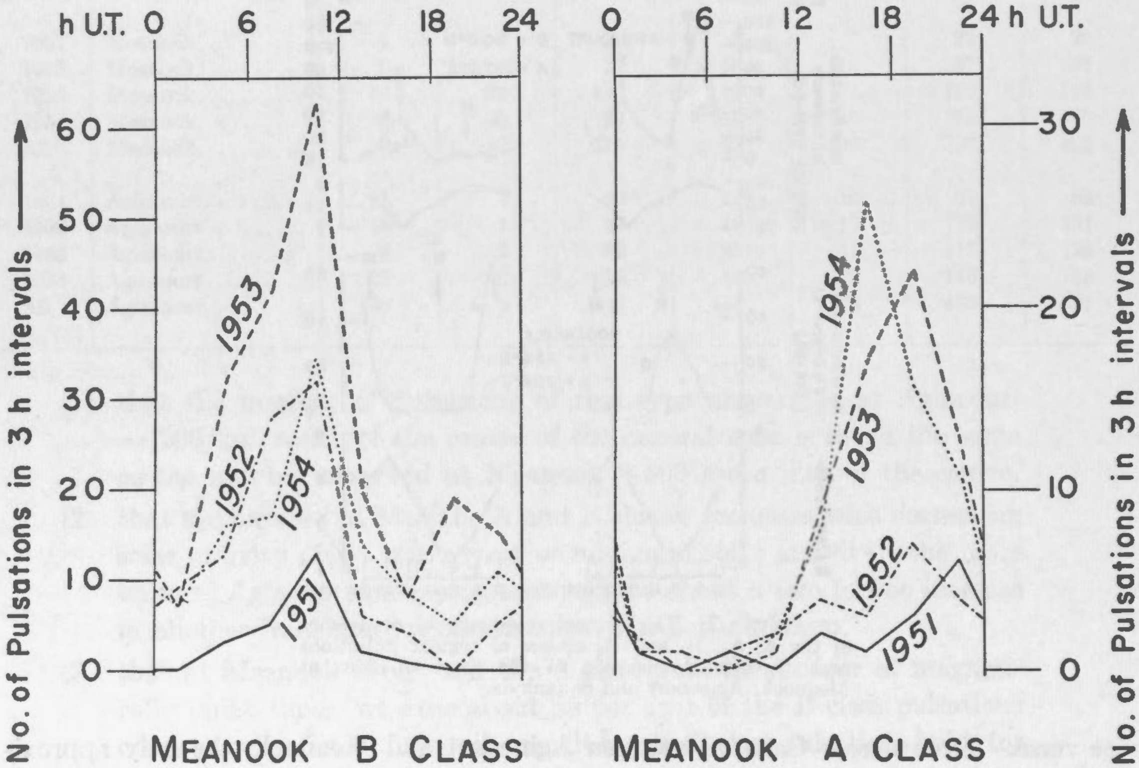

FIGURE 3. The diurnal frequency of occurrence of the A and B classes of regular pulsations at Meanook during the years 1951, 1952, 1953, and 1954.

The seasonal changes in the diurnal frequency of occurrence were investigated; generally the same results were obtained in all seasons for the more numerous B class pulsations. In all the years, it was found at Meanook that the sharpest maximum was obtained at the summer months and the broadest in the equinoxes.

The total number of pulsations of the two classes occurring in the different seasons is shown in Table III. Inconsistent results are obtained at the two locations. At

TABLE III

THE SEASONAL DISTRIBUTION OF REGULAR PULSATIONS AT MEANOOK AND AGINCOURT DURING 1951-54

	Meanook			Agincourt		
	A	B	Total	A	B	Total
Winter	41	122	163	22	149	171
Equinox	32	130	162	27	172	197
Summer	29	135	164	16	135	151

Meanook a seasonal variation in total number cannot be detected, that of the A class being opposite to that of the B class. There is a suggestion which is confirmed by examining the individual yearly data that the daytime A class is relatively more frequent in the winter months than in the equinoctial and summer months. At Agincourt there appear to be more pulsations in the equinoctial months than in the winter or summer months, but the variation is not large and both the A and B classes change together.

The average periods of the two classes appear to be different, the A class having a mean (and most probable) period smaller than the B class at both locations. The differences appear to be somewhat smaller at Agincourt than at Meanook. Table IV shows this trend is present every year, and Figure 4 shows a number-versus-period distribution curve for both locations. Figure 4 shows that the rapid decrease in number of pulsations

TABLE IV

THE AVERAGE PERIODS AND RANGES OF REGULAR PULSATIONS AT MEANOOK AND AGINCOURT DURING 1951-1954

	Average Period in Minutes				Average range △F in Gammas			
	Meanook		Agincourt		Meanook		Agincourt	
Year	A	B	A	B	A	B	A	B
1951	1.2	1.9	1.4	1.7	17	12	10	10
1952	1.3	1.9	1.4	1.8	12	15	9	9
1953	1.4	1.9	1.3	1.6	12	13	10	9
1954	1.1	1.5	1.2	1.5	13	15	10	9
All	1.3	1.8	1.3	1.6	13	14	10	9

with very short periods is real and is not an effect produced by the lower limit of resolution using standard-run magnetograms. The different average periods of the two classes produce a real diurnal variation in mean period which can be discerned on scatter diagrams for both observatories. Whilst the difference in mean period between the two classes seems real, it is not thought that the variations from year to year shown in Table IV, in the mean period of both classes, are significant. Figure 4 also suggests that the variation in period of regular pulsations is somewhat greater at Meanook than at Agincourt.

The maximum range of each pulsation was measured in three orthogonal field components. The average amplitude in each hour of the day is remarkably constant, but there is a small diurnal variation in amplitude because the B class of pulsations apparently have a mean amplitude somewhat larger than the A class at Meanook, and vice versa at Agincourt. Table IV shows that these mean differences are not very consistent from year to year at either station and it is not thought that there is any real difference. Amplitude distribution plots again show that there is a rapid decrease in the number of pulsations before the lower limit of measurement (3 gammas) is reached. The most probable range at both stations is between 5 and 10 gammas. Table IV refers to the total perturbing vector, ΔF, but essentially the same results are obtained if the larger horizontal component of perturbation is used. The largest pulsations are of the B class type and usually occur near the diurnal frequency maximum.

The seasonal variation of duration, period and amplitude was investigated in each year, and Table V summarizes the results for the four years. At Meanook there is no

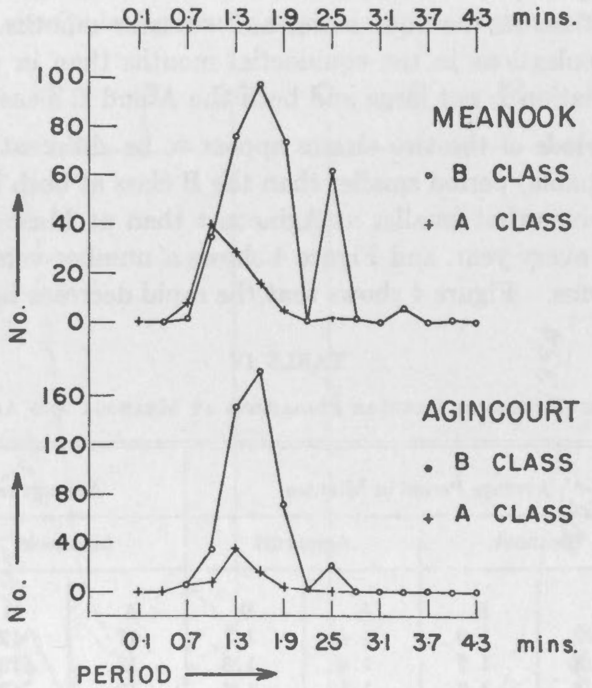

FIGURE 4. The number-period distribution curves for the A and B classes of regular pulsations at Meanook and Agincourt for the years 1951-54.

systematic difference in the mean period and duration from season to season and so the average in Table V for all years is very constant in each season. Much the same result is found for amplitudes: the vertical component, ΔZ, is between three to four times smaller than the total horizontal component, $\sqrt{(\Delta D)^2 + (\Delta H)^2}$, and at Meanook the average component along the meridian is always greater than that perpendicular to the meridian. In computing ΔF however, we neglect the effects of induction inside the earth. The penetration depth of electromagnetic waves with a period $\sim 10^2$ seconds is ~ 100 km., and so it seems unlikely that local crustal conditions at different continental observatories would produce seriously different local corrections in ΔZ and in ΔH, ΔD by the different effects of induction inside the earth. Consequently since $\Delta Z^2 << (\Delta H)^2 + (\Delta D)^2$ it

TABLE V

THE SEASONAL VARIATION IN PERIOD, DURATION AND RANGE OF REGULAR PULSATIONS AT MEANOOK AND AGINCOURT DURING 1951-54

Season	Observatory	T mins.	Duration mins.	ΔD	ΔH	ΔZ	ΔF	$\{(\Delta D)^2 + (\Delta H)^2\}^{\frac{1}{2}}/\Delta Z$
							gammas	
Winter......	Meanook...	1.7	51	7	10	4	13	3.3
Equinox.....	Meanook...	1.7	51	8	12	4	15	3.8
Summer.....	Meanook...	1.7	55	7	9	3	12	3.7
Winter......	Agincourt..	1.7	56	5	7	3	9	3.3
Equinox.....	Agincourt..	1.5	50	5	7	3	9	3.3
Summer.....	Agincourt..	1.5	40	6	7	2	9	3.9

seems likely that conclusions based on comparing ΔF cannot be seriously in error. It is clear that the effects of the highly conducting oceans may be serious on stations less than ~100 km. away.

At Meanook the mean amplitude of the disturbed and quiet sub-classes was determined for both the A and B types. It was found that

$$\frac{\Delta F\ (A_d)}{\Delta F\ (A_q)} = 1.0(5) \text{ and } \frac{\Delta F\ (B_d)}{\Delta F\ (B_q)} = 1.3(9).$$

This suggests that the strength of the B class sources increases with disturbance whereas no such effect is apparent for the A class.

At Agincourt a seasonal examination of the data for each season in each year shows that in general there are no outstanding seasonal variations in amplitude, duration and period, except that larger periods are apparently always found in the winter months, when the durations are also somewhat longer. Much the same ratio between the horizontal and vertical perturbations is found at Agincourt, and once again the mean perturbation is greater in the meridian.

The maximum range of any of the pulsations measured at Meanook was 33 gammas in ΔD, 47 gammas in ΔH and 19 gammas in ΔZ. At Agincourt the maximum pulsational range was only about half that at Meanook, 24 gammas in ΔD, 23 gammas in ΔH and 15 gammas in ΔZ.

THE OUTSTANDING GIANT PULSATIONS

For comparison with the infrequent shuttle-shaped giant pulsations, described in Scandinavia, the class A pulsations were re-examined and a selection made of those with a definite shuttle form; 47 were selected at Meanook and 24 at Agincourt. Approximately one half of them occurred at disturbed times at both locations. As found before, the diurnal variation of frequency of occurrence is somewhat later for the disturbed class than for the quiet class at both stations (20-21 hrs. U.T. for A_d, 15-17 hrs. U.T. for A_q at Meanook and 18-19 hrs. U.T. for A_d, 16-17 hrs. for A_q at Agincourt). The seasonal variation of the outstanding giant pulsations is the same as that of the A class discussed above. Since approximately half of the previously considered A class pulsations have been selected as outstanding pulsations at both locations, it is clear that the other statistical properties of the outstanding giant pulsations are also identical with the properties of the A class discussed above.

This suggests that the selection of precise shuttle-shaped forms has no intrinsic importance.

SIMULTANEOUS PULSATIONS AT MEANOOK AND AGINCOURT

A comparison of all the regular pulsations showed 22 coincident (i.e. within one or two minutes) pulsations with approximately the same period at both stations. This means that about 4 per cent of the pulsations have a linear extent of about 2700 kms. outside the auroral zone. During the months May, August, and October, 1954, 36 regular pulsations had been noted at Agincourt. On examination of the Meanook magnetograms at the same time, activity was observed on 29 occasions, often in the form of irregular perturbations on bay activity. Of the 43 listed for these trial months at Meanook, 33 could be traced on the Agincourt recordings during the same time intervals, but the perturbations were much reduced in amplitude, and irregular in form and often in period, and were therefore not noted as belonging to class A or B in the original magnetogram search.

Of 10 outstanding A_q giant pulsations found at Agincourt, 7 could be found at Meanook during the same universal time interval, but the pulsations appearing at Meanook occurred usually at disturbed times and occasionally with small amplitudes and could not have been counted as A_q pulsations at Meanook. Of the 24 outstanding A_q at Meanook, 13 were observed at Agincourt during the same time interval, but with ranges considerably less than 3 gammas. So far as can be determined, the periods were not always the same at the two locations.

REGULAR PULSATIONS AT BAKER LAKE AND RESOLUTE OBSERVATORIES

Baker Lake ($\Phi = 73.7°$N) is situated about as far north of the centre of the auroral zone, as Meanook is to the south, and disturbance characteristics there have been described by Whitham and Loomer (1957) as transitional between the auroral zone and the geomagnetic polar cap. Resolute ($\Phi = 83.0°$N) is situated well inside the polar cap. Previously no giant pulsations had been reported for such high latitude stations.

At Resolute, no definite regular pulsations of the types considered were found. The Baker Lake magnetograms were examined for regular pulsations occurring simultaneously with Meanook. Only 10 cases were found, and of these only 4 could possibly be identified as B class pulsations, the remainder being quite irregular. In one of these 10 cases, a pulsation also occurred at Agincourt during the same time interval. In most cases the periods of the pulsations observed at Baker Lake were too short to be measured using standard-run magnetograms: it seems therefore certain that shorter periods occur at Baker Lake than at Meanook for the 1 per cent of pulsations appearing at the same time. The high level of disturbance at Baker Lake and the uneven quality of the magnetograms may help explain the small number of regular pulsations which were found, but in any case regular pulsations are very infrequent inside the auroral zone.

SUMMARY OF RESULTS

It is considered that the above analysis supports the division, first suggested by Sucksdorff (1939), of regular pulsations in two classes, distinguishable by different form of amplitude envelope, and showing some distinctly different properties. Outstanding among these are the different daily variation of occurrence, and the different mean periods. As discussed above the results obtained from magnetic observatories in Canada considered with the published results from one Scandinavian station show that the pulsations discussed here are neither world wide phenomena occurring at the same universal time, nor local time (or local geomagnetic time) effects. A more complex explanation seems required, in which the occurrence of major sources at any location may prove to be a function of the latitude of the station as well as its longitude. At both stations, in each day there appear to be two preferred resonant frequencies occurring at different times of the day. So far as we can determine these two preferred frequencies are identical at both stations.

The two classes do however possess many common features which are subject to wide statistical fluctuations. Notable among these are the solar cycle dependence, very little systematic departure in mean range, no very marked or persistent seasonal variation in number, and the fact that the total horizontal field perturbation is always several times larger than the vertical field perturbation. In addition the average field perturbation in the plane of the meridian exceeds that at right angles to the meridian.

The regular pulsations described herein are not infrequent phenomena and of the order of 100 per year can be observed in Canada south of the auroral zone. It is considered that the infrequent Rolf or giant pulsations are best regarded as belonging to a sub-class of class A with a particularly well developed shuttle-shaped envelope and large amplitude.

South of the auroral zone, about 4 per cent of the pulsations measured at one location are visible as regular pulsations at the other location 2700 km. away. However, in a trial sample, about 80 per cent of the pulsations noted at one site do appear at the other location, but in a form not measurable as a regular pulsation. Furthermore the periods are not necessarily the same. Hence we must conclude that the extent of the waves is generally considerably less than 2000 to 3000 kms., and that in this distance the resonant frequency and its sharpness can change appreciably and that the strength of the exciting sources considerably decreases. The very few regular pulsations observed inside the auroral zone suggests that a standing wave system across the zone is not a very likely explanation. A standing wave across the zone was suggested by Lehnert's (1956) longitudinal mode. Essentially the non-occurrence at very high latitudes of giant pulsations confirms the findings of the 2nd Polar Year, 1932-33.

A comparison with the properties suggested in Table I shows that, whereas the durations, periods, amplitudes, geographical extent and solar cycle dependence listed there are largely confirmed in Canadian auroral regions, the relationships to daytime and nighttime occurrence are not confirmed and pulsations of this sort can be found down to geomagnetic latitude $\Phi = 55.0°$N in Canada, even at a time of sunspot minimum.

DISCUSSION OF RESULTS

An attempt is made in this section to relate the observed characteristics to magnetohydrodynamic waves and their possible location, and to discuss the possible effects of ionosphere screening and the relationship of pulsations to magnetic disturbance.

Lehnert (1956) has shown that the periods and amplitudes of pulsations are reasonable for magnetohydrodynamic waves. Following his analysis, it can be shown that free oscillations may occur if the period $T \geq T_c$, where the critical period

$$T_c = \frac{\pi}{\mu\sigma V^2}$$

where μ is the permeability,

σ is the effective conductivity,

and V^2 is the square of the phase velocity of magnetohydrodynamic waves.

It can be shown that free oscillations appear most probable in the transverse mode in the F_2 layer, where $T_c \sim 40$ seconds only. When $T \sim 100$ secs., the wave-length is $\sim 2 \times 10^3$ kms. Since the long durations found indicate a standing wave phenomenon, the relationship between amplitude and period is not clear, but it seems possible that with decreasing period, the effects of wave damping might be to reduce the amplitude as e^{-z/z_0} where z_0 is the damping distance, and z_0 can be shown to be equal to

$$\frac{\mu\sigma V^3 T^2}{2\pi^2}$$

A scatter diagram of log $\triangle F$ against T^{-2} shows that for both the A and B class pulsations at Meanook, log F decreases with increasing T^{-2} and the best slope is $\sim 10^3$ secs^2. However the individual points for each pulsation are widely scattered. In the F_2 layer the theoretical value of the slope $\sim 3 \times 10^3$ secs^2. and this slope rapidly increases in lower ionospheric regions. This suggests that both classes of pulsations originate high in the ionosphere, and eliminates the possibility of explanations requiring the longitudinal mode in lower ionospheric regions.

It also is unlikely that magnetohydrodynamic waves in interplanetary space can provide a plausible explanation because, although T_c for such waves becomes very small, the wave-lengths become very large and as discussed earlier the observational evidence for widespread pulsations of the same period is very weak. However it does seem as if such waves might account for the geographically widespread micropulsations, not discussed here, and whose geographical spread is still in doubt.

Although the damping of a free magnetohydrodynamic oscillation is mentioned above, and used to suggest a high altitude for any standing wave system, there is another explanation of the observed amplitude-period trend. This could be produced by the screening effects of lower ionosphere levels. The influence of such screening may be written as $A(\omega) = A_0(\omega)e^{-\int_0^L (2\pi\mu\sigma\omega)^{\frac{1}{2}} dl}$ where $A(\omega)$ is the amplitude at the ground at angular frequency ω and $A_0(\omega)$ is the amplitude at the ground which would be obtained in the absence of shielding. Now $\int_0^L \sigma^{\frac{1}{2}} dl \approx L(\bar{\sigma})^{\frac{1}{2}}$ within a few per cent. Assuming the cross-conductivity to be the effective conductivity and using the ionospheric data listed by

Lehnert (1956), we find most of the shielding is caused by the upper ionospheric layers and the expression becomes $A(T) = A_0(T)e^{-25T^{-\frac{1}{2}}}$, and at $T \sim 100$ secs., the attenuation seems very large, some 92 per cent.

If we assume the primary sources have equal strength on the average, and if shielding were so important, it seems likely that the mean B class amplitude would appreciably exceed the mean A class amplitude at Meanook and Agincourt because of the difference in mean periods, and partly because the A class in Canada is a daytime phenomena whilst the B class is a nighttime class. Table IV indicates that no such very clear difference in amplitudes is found, and in any case $2\pi\,(\mu\,\bar{\sigma})^{\frac{1}{2}}\,L$ must be less than ~ 5.

Scatter diagrams of log $\triangle F$ against $T^{-\frac{1}{2}}$ were drawn and the inconclusive results obtained for all classes are illustrated in Figure 5, which shows the scatter diagram for the class of outstanding giant pulsations at Meanook. The best slope in Figure 5 indicates $2\,\pi\,(\mu\,\bar{\sigma})^{\frac{1}{2}}\,L \sim 9$ secs.$^{\frac{1}{2}}$. In view of the order of magnitude uncertainties in the conductivity this agreement might be considered quite satisfactory. Because a sharp decrease is found in the number of pulsations with very small amplitude before the 3-gamma level is reached, it appears unlikely that different amounts of ionospheric shielding can produce the apparent solar cycle variation.

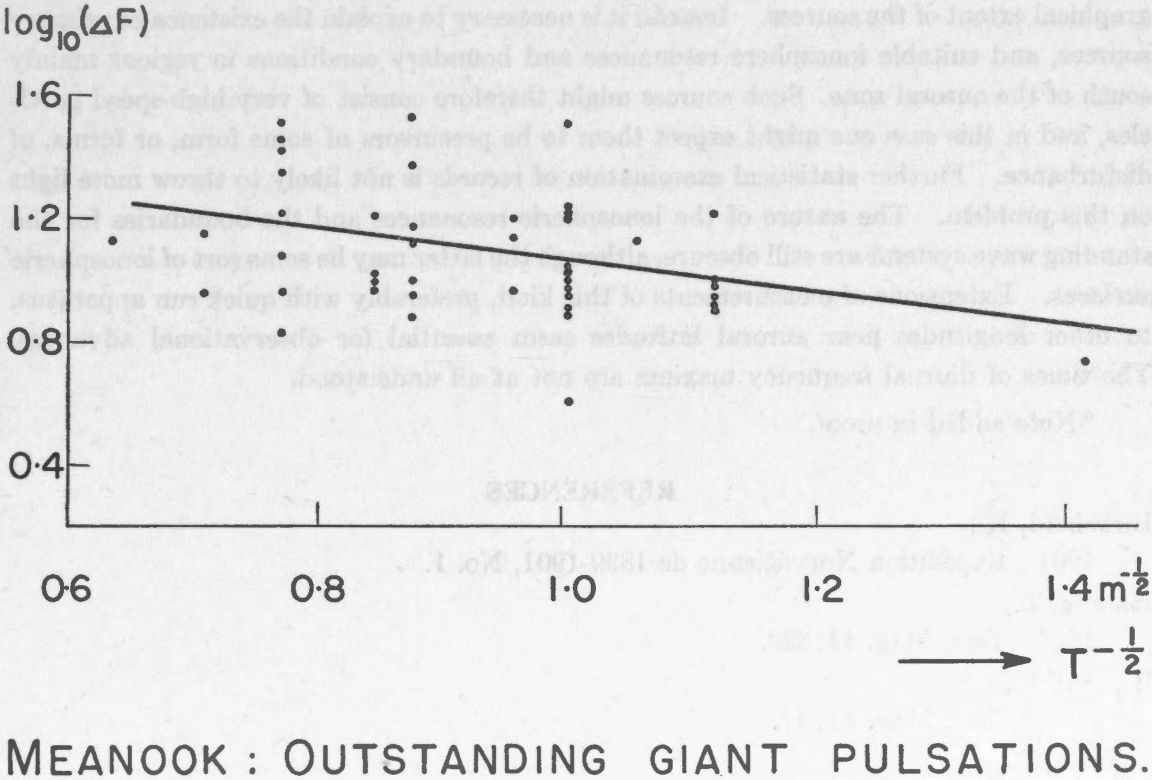

FIGURE 5. The scatter diagram relating log $(\triangle F)$ and $T^{-\frac{1}{2}}$ for the class of outstanding giant pulsations at Meanook.

Despite the attempts made to consider both classes at disturbed and quiet times it is difficult to associate either class in any certain way with disturbance. In particular the Agincourt results do not support the idea that the maximum frequency of occurrence of B class pulsations follows the maximum disturbance by a few hours, and between Scandinavia and Canada there is a reversal of the association of disturbed times and quiet times with the two classes of pulsations. Furthermore there appears to be an inverse relationship between solar activity and the number of sources. Hence the correlation with disturbance is indirect, and enhancement of conductivity by auroral discharges does not seem to be the major condition for a measurable pulsation to exist. Therefore the strength and number of primary sources seems of more importance. However, at Meanook, it was found that at times of disturbance there is appreciable enhancement of the amplitude of the B class pulsations, whereas no such enhancement occurs for the A class. It appears therefore that the strength of the sources may increase with disturbance at the usually disturbed time of day, but not at the usually quiet time of day. Because of this it is not possible to look for increasing screening effects of an enhanced conductivity. It has also been demonstrated that the diurnal frequency maximum of class A pulsations depends on the degree of magnetic disturbance.

In summary, magnetohydrodynamic waves in the upper parts of the ionosphere only can best explain regular oscillations. Oscillations in lower ionospheric layers, possible only when the conductivity is enhanced by auroral discharge, cannot explain the geographical extent of the sources. Instead it is necessary to explain the existence of primary sources, and suitable ionosphere resonances and boundary conditions in regions mainly south of the auroral zone. Such sources might therefore consist of very high-speed particles, and in this case one might expect them to be precursors of some form, or forms, of disturbance. Further statistical examination of records is not likely to throw more light on this problem. The nature of the ionospheric resonances and the boundaries for the standing wave systems are still obscure, although the latter may be some sort of ionospheric surfaces. Extensions of measurements of this kind, preferably with quick run apparatus, to other longitudes near auroral latitudes seem essential for observational advances. The times of diurnal frequency maxima are not at all understood.

* Note added in proof.

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** Recently J. A. Jacobs and T. Obayishi (Contract AF 19(604)-2147, Scientific Report No. 5) have considered transverse magnetohydrodynamic oscillations of the lines of force of the earth's magnetic field as an explanation of those pulsations in this frequency range of comparatively widespread geographical extent. As shown above, our studies indicate that such widespread effects in the amplitude range considered, are comparatively infrequent, indicating that transverse oscillations over a limited region only are most common. Observations at conjugate points (which are being made during the I.G.Y.) should clarify which oscillations correspond to ionospheric surfaces in one region as boundaries, and which correspond to ionospheric surfaces in opposite hemispheres as boundaries.*

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DIRECTION OF FAULTING IN SOME OF THE LARGER EARTHQUAKES OF 1955-1956

BY

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ABSTRACT

Fault-plane solutions are presented for fifteen of the larger earthquakes of 1955-1956, and the solutions are summarized in tabular form.

INTRODUCTION

The fault-plane project of this Observatory was recently examined in two papers (Hodgson, 1957; Hodgson and Adams, 1958) in which it was concluded that the techniques of the project had justified themselves sufficiently that the program should be continued, but that reflected phases should not be used. This is the second paper of a new series produced with this limitation in mind. The solutions have been based on P and PKP only, but in each case reflected phases reported in the questionnaires have been tested for consistency against the completed solutions. This has provided additional information on the reliability of these phases.

Because the earlier statistical study (Hodgson and Adams, 1958) suggested that all stations are not equally reliable and that good stations sometimes have their galvanometers accidently reversed, a new technique has been adopted in the present paper. Tentative solutions were made for as many of the earthquakes as possible. Each station was then tested for consistency with these solutions, and a chronological list was made showing the consistent and inconsistent observations for each station. Stations which were inconsistent about as often as they were consistent were given very low weight in subsequent revision of the solutions. If a particular station had been consistent most of the time up until a certain date, and then became inconsistent most of the time, a letter was sent to the station suggesting that their galvanometer might have become reversed and indicating the approximate date of this. There were nine such stations, on five different continents. Our suspicions were confirmed at seven of the stations and proved to be unfounded for one; the ninth station has not replied. The solutions were then all remade in the light of these findings; reversed observations were corrected and stations with random observations were given very low weight. The fact that our suspicions had been incorrect in one case led us to discard the solutions on which that suspicion had been based. This new method permits an earlier appraisal of station reliability and a more accurate determination of solutions.

Data used in this paper derive from questionnaires circulated in September, 1956, and in May, 1957. These covered 29 principal earthquakes and 7 aftershocks. Fifteen solutions have been obtained, a much smaller percentage than usual. This is largely due to the fact that all the aftershocks and four of the principal shocks were too small to provide sufficient data. Two other earthquakes failed to provide unique solutions; the suggestion will be made that these earthquakes resulted from some mechanism other than failure under a couple.

PRESENTATION OF THE DATA

Table I lists in three groups the 29 principal earthquakes for which solutions were attempted. The first group contains earthquakes for which no solutions could be obtained,

TABLE I

LIST OF THE EARTHQUAKES CONSIDERED

Date	H (G.M.T.)	Epicentre		Focal Depth	Magnitude	Remarks
		φ	λ			
Earthquakes for which solutions have not been obtained						
Sept. 26, 1955......	08:28:20	15½°N	92½°W	0.03R	6¾	Conflict of data
Oct. 10, 1955......	08:57:44	5°S	153°E	0.00R	7¼	Conflict of data
Dec. 7, 1955......	15:03:11	26½°N	142½°E	0.00R	6¾ to 7	Conflict of data
Jan. 16, 1956......	23:37:37	½°S	80½°W	0.00R	7¼ to 7½	Conflict of data
Mar. 13, 1956......	13:13:10	7°N	82°W	0.00R	7	Too few and conflicting data
Mar. 22, 1956......	06:33:55	3½°S	79°W	0.01R	6¾ to 7	Conflict of data
Apr. 18, 1956......	11:00:13	52°N	178°W	0.00R	6¾	Too few data
June 9A, 1956.....	10:08:32	30½°S	70½°W	0.02R	6¾	Too few and conflicting data
June 9B, 1956.....	23:13:51	35½°N	67½°E	0.00R	7¼ to 7½	Conflict of data
July 17, 1956......	07:34:07	7°S	126½°E	0.07R	6¾	Conflict of data
July 18, 1956......	06:19:15	5°S	130°E	0.00R	7¼ to 7½	Conflict of data
July 23, 1956......	19:25:58	24°S	112°W	0.00R	6¾	Too few data
Earthquakes for which solutions have been obtained						
Aug. 16, 1955......	11:46:58	6°S	155°E	0.03R	7½	
Aug. 21, 1955......	17:33:58	3°S	137½°E	0.00R	6¾ to 7	
Aug. 28, 1955......	20:13:30	14°N	91°W	0.01R	6¾	
Sept. 12, 1955......	06:09:20	32½°N	30°E	0.00R	6¾	
Oct. 13, 1955......	09:26:44	9½°S	161°E	0.00R	7	
Nov. 10, 1955......	01:44:04	15°S	174°W	0.01R	7 to 7½	
Nov. 22, 1955......	03:24:00	24½°S	123°W	0.00R	6¾ to 7	

TABLE I—*Concluded*

LIST OF THE EARTHQUAKES CONSIDERED

Date	H (G.M.T.)	Epicentre		Focal Depth	Magnitude	Remarks
		φ	λ			
Earthquakes for which solutions have been obtained—concluded						
Jan. 8, 1956......	20:54:13	19°S	70°W	0.00R	7¼	
Jan. 10, 1956......	08:52:36	25°S	176°W	0.00R	7½	
Jan. 31, 1956......	09:17:11	4°S	152°E	0.06R	7 to 7¼	
Feb. 1, 1956......	13:41:44	19°N	145½°E	0.05R	6¾ to 7	
Feb. 9, 1956......	14:32:40	31½°N	116°W	0.00R	6¾	
Feb. 18, 1956......	07:34:16	30°N	137½°E	0.07R	7¼ to 7½	
July 9A, 1956.....	03:11:39	37°N	26°E	0.00R	7½	
July 9B, 1956.....	09:56:13	20°N	73°W	0.01R	6½ to 6¾	
Earthquakes for which the data were sufficient but inconsistent						
Nov. 23, 1955......	06:29:29	50½°N	157°E	0.005R	7	Different Mechanism (?)
May 23, 1956......	20:48:30	15½°S	179°W	0.07R	7 to 7¼	Different Mechanism (?)

and gives reasons for the failure: the second group lists earthquakes for which solutions were obtained: the third group consists of two earthquakes for which the data were sufficient but inconsistent. Two of the earthquakes listed in the Table occurred on the same date. The earlier has been called A, the later B.

In the earthquakes of the third group one circle could be defined for each earthquake but the second circle could have been drawn in either of two quite different positions. No justification could be found for selecting one position rather than the other, since both involved sacrificing a small group of reliable stations. The distribution of data in these unsolved 'quakes may indicate a mechanism more complex than failure under a couple. To facilitate additional study of this problem, first motion data, epicentral distances, and azimuths are given in Table II for all stations recording the two earthquakes. It is interesting to note that the earthquake of Nov. 23, 1955, occurred at a focal depth of 60 km. in the Kamchatka region where five similar unsolved earthquakes took place in 1953, (Hodgson, 1956). The shock of May 23, 1956, was the first of this type in the Fiji Islands.

TABLE II

Distance, Azimuth and First Motion Data for Two Anomalous Earthquakes

A negative sign indicates an azimuth measured west of north

EARTHQUAKE	Nov. 23, 1955			May 23, 1956		
STATION	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion
Aberdeen	71.2	− 12.0	C	138.4	+ 2.4	C'_1
			CC			CC
Abuyama	—	—	—	66.3	− 40.0	C
Alberni	—	—	—	80.3	+ 32.8	D
Alger	—	—	—	159.0	− 4.6	C'_1
						D'_2
Alicante	89.5	− 17.7	C	157.3	+ 2.9	C'_1
						CC
Almeria	91.1	− 16.5	D	158.6	+ 7.5	D'_1
Angra do Heroismo	—	—	—	146.1	+ 41.7	C'_1
Apia	—	—	—	7.3	+ 77.0	C
Arcata	—	—	—	76.0	+ 40.0	C
Ashkhabad	—	—	—	125.0	− 54.4	C'_1
Astrida	115.0	− 61.5	D'_1	146.1	−120.3	C'_1
						cC'_1
						cCC
Athens	82.7	− 35.7	C	150.1	− 38.1	C'_1
Auckland	—	—	—	22.0	−166.6	D
						DD
Bandung	71.3	−127.6	C	—	—	—
Banff	—	—	—	86.5	+ 34.4	C
Barrett	63.6	+ 70.2	C	—	—	—
Basel	78.9	− 20.7	C	147.8	− 8.6	C'_1
Belgrade	77.7	− 30.2	D	146.6	− 25.9	C'_1
Bensberg	—	—	—	144.5	− 6.8	C'_1
Berkeley	56.6	+ 69.6	C	75.3	+ 43.4	C
Bermuda	89.5	+ 34.1	C	118.8	+ 61.3	D
Bologna	80.8	− 24.4	D	149.8	− 6.5	C'_1
						cC'_1
Boulder City	62.2	+ 66.5	C	79.5	+ 48.0	C
Bozeman	57.8	+ 55.9	C	86.4	+ 40.6	C
Butte	56.9	+ 56.4	C	85.7	+ 39.9	C
Cartuja	91.1	− 15.6	C	158.1	+ 9.9	D'_1
			DD			C'_2
			CCC			dD'_1
			PcP=D			CC
Cheb	—	—	—	144.5	− 13.0	C'_1
						DD
						cCC
Chihuahua	72.7	+ 66.0	D	83.3	+ 57.7	C
Christchurch	95.0	+168.5	D	28.8	−167.5	D
Clermont	—	—	—	150.1	− 3.1	C'_1
Cleveland	—	—	—	105.8	+ 50.8	D
						dD
						D'_1
Cobb River	—	—	—	26.4	−165.9	D
						cC
Coimbra	88.8	− 11.2	D	154.2	+ 16.5	C'_1
						C'_2
College	31.8	+ 42.3	C	—	—	—
Collmberg	73.9	− 22.8	C	143.4	− 12.9	C'_1
						CC

TABLE II—*Continued*

Distance, Azimuth and First Motion Data for Two Anomalous Earthquakes

A negative sign indicates an azimuth measured west of north

EARTHQUAKE	Nov. 23, 1955			May 23, 1956		
STATION	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion
Columbia	81.7	+ 45.3	C	105.2	+ 58.4	C
Copenhagen	70.1	− 20.6	D	139.2	− 10.2	Cí dDí CC
Corvallis	—	—	—	77.4	+ 39.0	C
De Bilt	74.9	− 17.8	C	143.6	− 4.6	Cí dDí DD
Djakarta	71.1	−126.5	C	73.1	− 91.8	C
Durham	73.6	− 13.1	C CC	140.9	+ 2.2	Cí DD
Eureka	59.2	+ 64.3	C	80.3	+ 44.6	C
Fayetteville	—	—	—	95.1	+ 53.9	D
Florence	81.6	− 24.6	C	150.8	− 15.5	Cí
Florissant	73.1	+ 48.8	D PcP = C	—	—	—
Fresno	58.8	+ 69.0	C	76.4	+ 45.5	C
Frunse	54.3	− 64.2	C	112.5	− 49.9	C
Fukuoko	25.9	−121.2	C	68.6	− 43.8	C
Goris	71.8	− 49.8	C	134.0	− 49.9	Cí
Guadalajara	—	—	—	82.7	+ 66.1	C
Halifax	78.8	+ 28.2	C	119.0	+ 47.1	Cí
Hawaii	46.0	+112.6	C	42.3	+ 30.4	C
Helwan	—	—	—	148.7	− 58.2	Cí
Hermanus	—	—	—	127.2	−161.1	DDD
Hong Kong	43.7	114.4	C	75.4	− 61.8	C
Honolulu	—	—	—	42.3	+ 30.4	C
Horseshoe Bay	—	—	—	81.2	+ 33.3	C
Hungry Horse	54.6	+ 55.1	C	—	—	—
Irkutsk	32.4	− 66.4	C	94.1	− 37.0	C
Isabella	60.3	+ 69.0	C	—	—	—
Istanbul	—	—	—	144.9	− 38.7	Dí
Jerusalem	83.4	− 47.2	D	144.9	− 56.9	Dí
Jujhno-Sakhalinsk	10.0	−105.0	C	—	—	—
Kaimata	—	—	—	28.2	−165.1	D cC
Karapiro	90.0	+165.3	C	22.8	−168.9	D cC
Karlsruhe	77.2	− 20.9	D PcP = D	146.3	− 9.2	Cí dDí DD
Kew	76.5	− 14.6	C	144.3	+ 1.4	Cí DD
Kirkland Lake	70.2	+ 36.6	C	107.6	+ 44.0	CC
Kirovabad	—	—	—	133.6	− 48.5	Cí
Kiruna	57.6	− 18.2	C	126.5	− 9.2	Cí
Kochi	24.3	−126.1	C	66.6	− 42.4	C
Ksara	81.2	− 46.5	C CC	143.7	− 54.0	Cí
La Paz	130.7	+ 62.9	Dí CC	104.8	+112.0	D dD DD

TABLE II—*Continued*

Distance, Azimuth and First Motion Data for Two Anomalous Earthquakes

A negative sign indicates an azimuth measured west of north

Earthquake	Nov. 23, 1955			May 23, 1956		
Station	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion
La Plata	150.4	+ 71.2	D_i'	—	—	—
Lembang	71.4	−127.6	C	72.0	− 92.6	C
Lisbon	90.3	− 10.9	D	155.3	+ 19.0	C_i'
						cC_i'
						dD_i
Lwiro	—	—	—	147.2	−120.7	C_i'
						cC
						CC
						cCC
Macquarie Island	—	—	—	42.3	−161.2	D
						cC
						CC
						DDD
Malaga	91.7	− 15.0	D	158.5	+ 11.5	D_i'
			CC			D_i
			DDD			
Manila	46.3	−128.0	D	66.5	− 66.5	C
Manzanillo	—	—	—	81.3	+ 67.4	C
Matsushiro	19.7	−129.2	C	65.6	− 36.9	C
Mazatlan	—	—	—	80.9	+ 62.8	C
M'Bour	115.3	− 6.5	CC	—	—	—
Melbourne	88.8	−170.7	C	38.7	−132.0	D
						dD
Merida	87.9	+ 59.0	D	95.1	+ 69.7	C
Messina	85.3	− 29.7	C	154.2	− 27.2	C_i'
Mineral	55.5	+ 66.8	C	77.1	+ 41.5	C
Miyako	—	—	—	66.0	− 32.2	C
Miyazaki	—	—	—	66.9	− 44.7	C
Monaco	82.5	− 22.0	C	151.6	− 10.2	C_i'
Moscow	62.8	− 33.9	D	—	—	—
Mount Hamilton	57.4	+ 69.7	C	75.4	+ 44.2	C
						dD
Nagoya	—	—	—	65.5	− 38.9	C
Neuchatel	79.4	− 20.5	C	148.6	− 8.0	C_i'
New Plymouth	—	—	—	24.3	−167.0	D
Noumea	73.5	+170.7	C	—	—	—
			dD			
			PcP=D			
			pPcP=C			
Oaxaca	—	—	—	87.5	+ 71.8	C
Ottawa	74.1	+ 35.6	C	110.3	+ 46.8	C
Palisades	78.4	+ 36.8	C	111.5	+ 51.7	C
			CC			cC
						C_i'
						CC
Palo Alto	—	—	—	75.1	+ 43.6	C
Palomar	63.0	+ 70.0	C	—	—	—
Pasadena	61.7	+ 70.1	C	76.2	+ 48.1	C
Pavia	80.6	− 22.6	C	149.8	− 11.5	C_i'
						cC_i'
Perth	—	—	—	60.8	−118.2	D
						cC

TABLE II—*Continued*

Distance, Azimuth and First Motion Data for Two Anomalous Earthquakes

A negative sign indicates an azimuth measured west of north

Earthquake	Nov. 23, 1955			May 23, 1956		
Station	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion
Pittsburgh	76.6	+ 41.2	C	106.7	+ 51.9	D
Prague	—	—	—	144.0	− 15.0	C'_1
Quetta	67.4	− 70.0	C	118.3	− 64.3	C'_1
						cC
Rabaul	—	—	—	30.2	− 71.4	C
Rapid City	—	—	—	90.9	+ 44.4	D
Rathfarnham	—	—	—	142.2	+ 7.0	D'_1
						cC'_1
						DD
Relizane	—	—	—	160.2	+ 1.1	D'_1
Reno	57.0	+ 66.6	C	77.7	+ 42.9	C
Resolute	56.4	+ 20.6	C	103.3	+ 15.8	C
Reykjavik	65.8	− 0.8	D	129.0	+ 12.7	C'_1
Riverside	62.1	+ 69.7	C	—	—	—
Riverview	84.2	−175.2	C	32.5	−129.3	D
			PcP=D			dD
Rome	—	—	—	152.1	− 18.7	C'_1
Saint Louis	73.4	+ 48.8	D	98.8	+ 52.3	D
			PcP=C			dD
						CC
Salt Lake City	60.7	+ 60.7	C	83.7	+ 44.8	C
San Juan	—	—	—	116.3	+ 76.8	C'_1
Santa Clara	—	—	—	75.2	+ 43.9	C
Sapporo	13.2	−119.5	C	68.7	− 30.3	C
Scoresby Sund	59.3	− 0.6	D	123.4	+ 9.0	D'_1
Seattle	50.6	+ 60.0	C	80.9	+ 35.0	C
Semipalatinsk	46.8	− 59.3	C	108.6	− 41.6	C
Sendai	—	—	—	65.3	− 33.9	C
Seven Falls	74.3	+ 31.7	D	—	—	—
Shasta	54.8	+ 66.9	C	76.9	+ 40.8	C
Shawinigan Falls	—	—	—	112.5	+ 45.6	C
						CC
Skalnate Pleso	74.0	− 28.1	D	143.1	− 21.4	C'_1
Skalstugan	—	—	—	131.6	− 7.0	C'_1
Spring Hill	81.0	+ 52.2	C	—	—	—
Stara Dala	75.7	− 27.4	D	144.9	− 20.5	C'_1
State College	77.2	+ 39.7	D	108.4	+ 51.8	D
						CC
Strasbourg	77.8	− 20.6	C	146.8	− 8.4	C'_1
						cC'_1
						CC
						dDD
Stuttgart	77.2	− 21.4	C	146.4	− 10.1	C'_1
Tacubaya	84.0	+ 67.1	D	86.0	+ 68.6	C
Takamatsu	—	—	—	66.7	− 41.3	C
Tamanrasset	—	—	—	171.7	− 30.3	C'_1
Tashkent	58.3	− 62.7	C	—	—	—
			CCC			
Tinemaha	59.5	+ 67.7	C	—	—	—
Tokyo	19.6	−133.8	C	64.1	− 36.7	C
Toledo	88.5	− 14.7	C	155.4	+ 9.1	C'_1
Tongariro	—	—	—	24.2	−171.1	D

TABLE II—*Concluded*

Distance, Azimuth and First Motion Data for Two Anomalous Earthquakes

A negative sign indicates an azimuth measured west of north

Earthquake	Nov. 23, 1955			May 23, 1956		
Station	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion
Trieste	79.0	− 25.5	C	148.4	− 17.0	C'_i
Tsukuba	—	—	—	64.4	− 36.0	C
Tuai	—	—	—	23.3	−172.7	C
Tucson	67.3	+ 66.9	C	80.9	+ 52.9	C
Uccle	—	—	—	144.9	− 3.8	C'_i
Ukiah	—	—	—	75.4	+ 41.8	C
Uppsala	65.2	− 21.4	C	134.3	− 11.9	C'_i
Uvira	—	—	—	146.2	−121.9	C'_i CC
Vera Cruz	—	—	—	88.8	+ 69.9	C
Victoria	49.5	+ 59.7	C	80.8	+ 33.9	C
Vienna	76.0	− 26.2	C	145.1	− 18.2	C'_i
Wellington	93.2	+166.6	C	26.2	−169.4	D
Weston	78.3	+ 34.3	C cC	—	—	—
Witteveen	—	—	—	142.8	− 5.8	C'_i DD
Woody	60.1	+ 69.3	C	—	—	—
Zagreb	78.1	− 26.8	C	—	—	—

The data on which the 15 solutions are based are given in Table III. The notation in Tables II and III is the same as in previous papers.

TABLE III

Data on which the Solutions are Based

STATION	Aug. 16, 1955	Aug. 21, 1955	Aug. 28, 1955	Sept. 12, 1955	Oct. 13, 1955	Nov. 10, 1955	Nov. 22, 1955	Jan. 8, 1956	Jan. 10, 1956	Jan. 31, 1956	Feb. 1, 1956	Feb. 9, 1956	Feb. 18, 1956	July 9A, 1956	July 9B, 1956
Aberdeen	CC	(CC)	(D)	(C) DDD	—	(C_1') (DD)	CC	—	(D_2')	—	—	—	C (CC) DDD	C	D CC
Abuyama	—	—	—	—	—	—	—	—	—	—	—	—	C	—	—
Aikawa	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Ajiro	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Akita	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Alger	—	—	—	—	C_1'	—	—	D	—	—	—	—	—	—	D
Alicante	C_1' (cC_1')	C_1'	—	D	—	D_1'	—	(C)	(C_1')	D_1'	(C_1')	D	(C)	C	—
Almeria	(D_1')	C_1'	D	D	(D_1')	D_1'	—	(C)	D_1'	D_1'	(C_1') (DD)	(C) (CC)	(C) (CC)	—	(C)
Angra do Heroismo	—	—	(C)	—	—	—	—	—	—	—	—	—	—	(D)	—
Aomori	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Apia	(C)	—	—	C_2'	C cC DD	D	(C)	—	C	C	—	C	C	D_2'	—
Ashkhabad	—	—	—	—	—	—	—	—	—	—	—	—	D	—	—
Astrida	C_1'	—	C_1'	C	C_1' DD	—	—	(DD)	D_1'	D_1'	D_1'	C_1'	(C) CC	D	CC
Athens	(D_1')	—	—	D	C_1'	D_1'	C_1'	—	—	—	—	—	—	C	(C)
Auckland	—	—	—	—	C	C	—	—	D	—	—	—	D	—	—
Bandung	—	—	—	—	—	—	—	(C_1')	—	—	—	—	D	—	—
Banff	D	—	C	C	C	D	D	C	—	D	D	D	—	—	—
Barcelona	—	—	—	—	—	—	—	—	—	—	—	D	—	—	—
Barrett	D	—	—	—	C	—	D	—	—	—	—	D	—	—	—
Basel	(D_1')	C_1'	(D)	D	C_1'	D_1'	—	D	D_1'	—	D	C	(C)	C	D
Belgrade	C_1'	—	C	D	(D_1')	D_1'	C_1'	—	D_1'	—	—	(C)	D	(D)	D
Bensberg	—	—	—	D	—	—	—	D	—	—	D	—	—	—	—
Berkeley	D	C	C	—	C	(C)	D	C	C	D	D (dD)	D	C	(CC)	D
Bermuda	—	—	(C)	C	C_1'	D_1'	(C)	D	—	—	—	C	—	C	C
Besancon	—	—	—	—	—	—	D	—	—	—	—	—	—	—	—
Big Bear	—	—	—	—	—	—	—	—	—	—	—	D	—	—	—
Bologna	—	—	—	D	—	—	—	—	—	—	—	—	—	C	—
Boulder City	D	—	C	C	C	D	(C)	C	C	D	D	D	C	D	D
Bozeman	D	—	C	(D)	C	D	(C)	C	(D)	D	D	D	C	(C)	D
Bucarest	—	—	—	C	—	(C_1')	C_1'	—	—	—	—	—	—	—	—
Butte	(C)	C	C	C	C	(C)	D	C	C	D	(C)	D	C	D	D
Cartuja	(D_1') dD_1' CC	(D_1') DD cCC CCC	(C) CC DDD (PcP=D)	—	C_1' (CC)	(C_1') dD_1' (DD)	—	(C)	D_1' (D_2') DD	—	—	(C)	(CC) dDD (DDD) dDDD	D	(C) (CC) (PcP=D)

TABLE III—*Continued*

Data on which the Solutions are Based

Station	Aug. 16, 1955	Aug. 21, 1955	Aug. 28, 1955	Sept. 12, 1955	Oct. 13, 1955	Nov. 10, 1955	Nov. 22, 1955	Jan. 8, 1956	Jan. 10, 1956	Jan. 31, 1956	Feb. 1, 1956	Feb. 9, 1956	Feb. 18, 1956	July 9A, 1956	July 9B, 1956
Cheb	—	—	—	—	—	—	—	—	—	—	D CC	—	D (dD) DD (DDD)	—	—
Chicago (U.S.C.G.S.)	—	—	—	—	—	—	—	—	D	—	—	—	—	—	D
Chichibu	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Chihuahua	—	—	—	—	—	—	D	C	—	—	—	(C)	DD	(CC)	—
China Lake	—	—	—	—	C	—	—	—	—	—	—	—	—	—	—
Chinchina	—	—	—	—	—	—	—	D	—	—	—	—	—	—	—
Christchurch	—	—	—	—	C (DDD)	—	D	—	C	—	—	—	D	—	—
Chosni	—	—	—	—	—	—	—	—	—	—	—	—	D	—	—
Clermont	—	—	—	—	—	—	—	—	—	—	—	—	—	C	D
Cleveland	C'_1 cC CC	C'_1	—	C	(D'_1) (CC)	D CC	(C)	D	—	—	D'_1 (DD)	C	(D) (dD)	C	—
Cobb River	C	D	—	C'_1	C	—	—	—	—	—	—	—	—	—	—
Coimbra	C'_1	—	D	D	C'_1 C'_2	(C'_1) (C'_2)	—	D	DD	—	—	C	—	C	D
College	C	—	C	(D)	(D)	D	C	C	C	D	D	D	C	—	D
Collmberg	—	—	—	—	(D'_1)	—	—	(C) (CC)	—	—	D CC	(C) (CC)	D DD	—	D (DD)
Columbia	—	—	—	C	C	—	—	D	—	—	D'_1	C	—	—	D
Comitan	—	—	(D)	—	—	D	—	—	—	—	—	D DDD	—	(CC)	—
Copenhagen	C'_1	DD	C CC	—	—	(cC'_1) (DD)	DDD	(C) DD	D'_1	—	D (DD) (dD)	D	D (dD) DD	C	(C)
Corvallis	—	—	—	—	—	—	—	—	—	—	—	D	—	—	—
Dalton	—	—	—	—	—	—	—	—	—	—	—	D	—	—	—
De Bilt	—	—	—	D	C'_1	(C'_1)	—	D	D'_1	—	—	D	D	C	D
Djakarta	D	C	C'_1	C	C	C	—	D'_1	D	—	D	—	D	(C)	—
Durham	(D'_1) (DD) (dDD)	DD	(D)	D	—	D'_1	—	—	—	—	—	—	(C)	C (PcP=C)	D
Eureka	(C)	—	C	C	C	D	D	C	—	D	D	D	C	—	D
Fayetteville	—	—	—	—	—	—	—	(D)	—	D	(C)	—	—	—	—
Florence	C'_1 (cC'_1) (DD)	—	—	—	—	D'_1	—	D	—	—	D	—	(C)	—	D
Florissant	—	C'_1 (DD)	(C) (dDD)	(D) (DD)	C'_1 DD	D (DD)	D	—	D (DD)	—	(C) (dD) (DD)	C	—	—	(C)
Fort Tejon	—	—	—	—	—	—	—	—	—	—	—	D	—	—	—

Fresno	D	—	C	—	C	—	D	C	C	D	D	D	C	—	—
Frunse	D (cC)	—	—	—	C	—	—	—	—	—	D (dD)	—	(C)	—	—
Fukuoko	D	—	—	C	—	—	—	—	D	—	D	—	C	—	—
Fukushima	—	—	—	—	—	—	—	—	—	—	—	D	—	—	—
Funatsu	—	—	—	—	—	—	—	—	—	—	D	—	D	—	—
Goris	—	—	—	—	—	—	—	D_1' DD	—	—	D cC	—	(C) cC	—	D (DD)
Grahamstown	—	—	—	C	—	—	—	D	—	—	—	(C_1')	—	(C)	—
Guadalajara	—	—	D	—	—	—	—	—	—	—	—	D	—	—	—
Hachijo-Jima	—	—	—	—	—	—	—	—	—	—	—	—	(C)	—	—
Halifax	C_1' dD_1'	C_1'	D DD CCC	—	C_1'	—	—	C	—	—	(C_1')	(D)	DD	C	—
Hamada	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Hamburg	—	—	—	—	—	—	—	—	—	—	—	—	—	C	—
Hatinohe	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Hawaii	D	D	C	—	C	(C)	(D)	—	—	D	—	—	(C)	—	—
Helsinki	—	—	—	—	—	—	—	—	—	—	—	—	—	(D)	—
Helwan	—	—	—	—	C_1'	—	—	—	—	D_1'	D	—	—	D	D
Hermanus	—	—	CC	C	—	—	—	(C)	—	—	CC (CCC)	—	—	—	—
Hiroshima	—	—	—	(D)	—	—	—	(CC)	—	—	D	—	—	D	—
Hong Kong	D (cC)	C	—	—	C	—	—	—	D	D	D CC	—	D	—	—
Honolulu	D	D	(D)	—	—	—	—	—	(D)	—	D	—	—	—	C
Horseshoe Bay	D	—	C	—	C	—	C	(D)	—	D	D	D	C	D	D
Hungry Horse	(C)	C	C	C	C	D	(C)	C	C	D	D	D	C	D	D
Inawashiro	D	—	—	—	—	—	—	—	—	—	D	—	C	—	—
Irkutsk	D	(D)	—	C	C	D	D_1'	D_1'	—	D	D	—	C	D	—
Isabella	—	D	—	—	C	—	—	—	—	—	—	D	—	—	—
Istanbul	—	—	—	—	—	—	—	—	—	—	—	—	—	—	(C)
Izuhara	—	—	—	—	—	—	—	—	—	—	—	—	C	—	—
Jerusalem	—	—	—	(C)	—	(C_1')	—	(C_1')	—	—	(C)	—	(C)	(C)	—
Jujhno-Sakhalinsk	D	C	(D)	C	C	D	D_1'	D_1'	C	D	D	—	C	D	D
Kagoshima	—	—	—	—	—	—	—	—	—	—	D	—	C	—	—
Kaimata	—	—	—	C_1'	C	(D)	—	—	D	D	(C)	—	(C)	—	—
Kameyama	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Karapiro	C	D	—	C_1'	C	C	—	—	—	D	D	—	D	—	—
Karlsruhe	C_1' (DD)	DD	C (cC)	D	C_1' (CC)	D_1' (cC_1') (DD)	(D_1')	D (CC)	—	D_1'	(DD) (dD) (cCC)	D	D (dD)	C	D
Kew	C_1' (cC_1')	(D_1') DD	C (DD)	D	C_1'	D_1' (DD)	C_1'	D (dD) DD cCC CCC	D_1'	D_1'	D (DD) (CCC)	C	D (dD) (CC)	C	D dD (CC)
Kimberley	—	—	C_1'	(D)	(D_1')	—	(D_1')	(C)	—	(C_1')	(C_1')	(C_1')	—	(C)	—
Kirkland Lake	C_1' CC cCC	C_1'	C	C (cC)	—	—	(C)	D	—	D_1'	—	C	C (dD) (CC)	C	D
Kirovobad	—	C	—	(D)	—	—	—	—	—	—	—	—	—	D	D

TABLE III—*Continued*

Data on which the Solutions are Based

Station	Aug. 16, 1955	Aug. 21, 1955	Aug. 28, 1955	Sept. 12, 1955	Oct. 13, 1955	Nov. 10, 1955	Nov. 22, 1955	Jan. 8, 1956	Jan. 10, 1956	Jan. 31, 1956	Feb. 1, 1956	Feb. 9, 1956	Feb. 18, 1956	July 9A, 1956	July 9B, 1956
Kiruna	—	DD	C	C	C	—	C_1' (DD)	—	—	D_1'	D	(C)	C DD CCC	C	D
Kizil-Arvat	—	—	—	—	—	—	—	—	—	—	—	—	—	(C)	—
Kochi	—	—	—	—	—	—	—	—	—	—	D	—	C	—	—
Kofu	—	—	—	—	—	—	—	—	—	—	D	—	C	—	—
Ksara	C_1' CC (dDD)	C	(D)	—	(D) (CC)	D_1' dD_1' cCC	(D_1') C_2' CC	DD CCC	(C_2') CC	—	D (DD) cC	—	D (dD)	(C) DDD	(C) CC
Kumagaya	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Kumamoto	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
La Paz	C_1' DD	C_1' DD	(C) CC	—	C_1' (CC)	(D_1')	(D)	(D)	—	D_1' (DD)	D_1' (dD_1') (DD)	(C)	D_1' (cC_1')	D DD	C cC (CC) (cCC)
La Plata	—	C_1'	—	—	—	C_1'	—	D	—	—	—	—	D_1'	—	—
Lembang	D	—	C_1'	C	C	C	—	D_1'	—	D	—	—	D	D	C_1'
Lisbon	(D_1') CC	—	—	D	(D_1') C_2'	D_1' (C_2')	—	D DD	—	D_1'	(DD)	D	—	C (dD)	D
Lwiro	(D_1') (DD) (CCC)	(CC)	C_1'	C	C	—	C_1'	(DD)	(C_1')	D_1'	D_1'	C_1'	D (C_1') cC	D	C CC
Macquarie Island	C	—	—	—	—	—	—	—	(C)	—	—	—	(C)	—	—
Madras	—	—	—	—	—	—	—	—	—	—	—	C_1'	—	—	—
Maebashi	—	—	—	—	—	—	—	—	—	—	D	—	—	D	—
Malaga	C_1' (DD)	C_1' (CC) (DDD)	D CC	(C) PcP=C	C_1' (CC) CCC	D_1' (C_1') (DD)	—	D	D_1' (D_2') DD	D_1' (DD)	D_1' CC (CCC)	D DD CCC	(CC)	C (PcP=C)	D DD (DDD) PcP=D
Manila	D	—	—	C	C	—	—	—	—	D	—	—	D	—	—
Manzanillo	—	—	—	—	—	—	—	—	—	—	—	D	—	—	—
Matsumoto	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Matsushiro	D (dDD)	D	—	C	C	D	—	D_1'	—	D	D	C	C	D	C_1'
Mazatlan	—	—	—	—	—	—	—	C	—	—	—	D	—	—	—
M'Bour	C_1' (DD)	(D_2')	(cC)	D (cC)	C_1' C_2' DD	C_1' D_2' CC	—	D	(CC)	—	D_1'	D	D_1'	(D)	D
Melbourne	—	D	—	—	C	C	D	—	—	D CC dD	D cC (PcP=C)	—	D (CC) (PcP=C)	—	—
Merida	(D_1')	CC	D	—	—	D	—	D	—	—	—	D	—	(C)	C
Messina	—	—	—	D	C_1'	D_1'	—	—	—	—	—	—	D	C	—

Messstetten	—	—	—	(C)	—	—	—	—	—	—	—	—	—	C	—
Mineral	D	—	C	C	C	—	D	C	C	—	—	D	C	—	D
Mishima	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Mito	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Miyako	—	—	—	—	C	—	—	—	—	—	—	—	C	—	—
Miyasaki	—	—	—	—	—	—	—	—	—	—	D	—	C	—	—
Monaco	—	—	—	—	—	—	—	—	—	(C'_i)	—	—	—	—	D
Montreal	—	—	—	—	—	—	—	—	—	—	—	—	—	(D)	(C)
Mori	—	—	—	(D)	—	—	—	—	—	—	D	—	—	—	—
Morioka	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Moscow	(C)	(D)	C	C	C	D'_i	—	(C'_i)	—	(C)	D	D	C (dD)	C	—
Mount Hamilton	D	C	(D)	—	C	(C)	D	C	C	D	D	D	C cC	D	D
Muroran	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Murotemisaki	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Nagano	D	—	—	C	—	—	—	—	—	—	D	—	—	—	—
Nagasaki	—	—	—	—	—	—	—	—	—	—	D	—	—	D	—
Nemuro	—	—	—	C	—	—	—	—	—	—	D	—	—	—	—
Neuchatel	—	C'_i	C	D	—	D'_i	—	D	—	D'_i	—	—	D	—	D
New Plymouth	(D)	—	—	—	C	—	—	—	—	—	—	—	—	—	—
Noumea	C cC	C CCC PcP=C	—	—	C	C	—	(CC)	D	D DDD	—	—	D	—	—
Oaxaca	(DD)	—	D	—	—	D	—	C	—	—	—	—	—	—	—
Oita	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Omaezaki	—	—	—	—	(D)	—	—	—	—	—	D	—	D	—	—
Onahama	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Osaka	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Oshima	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Ottawa	—	(D'_i)	—	C	C'_i	—	D	D	—	D'_i	—	C	C	C	D
Palisades	C'_i (cC'_i) CC	C'_i	C DD	C	C'_i (CC)	D (cC) (DD)	D	D	(DD)	D	D CC (CCC)	C	cC	(D) (CC) CCC	D
Palo Alto	—	(DD)	(D)	—	—	—	—	—	—	D	D	D	—	—	D
Palomar	—	—	C	—	C	—	—	—	—	—	—	D	—	—	—
Paris	—	—	(D)	D	—	—	—	—	D'_i	—	D	—	—	—	—
Pasadena	D	D	C	—	C	D	D	C	D	D	D	D	D	D	D
Pavia	—	—	C	D	—	D'_i	—	—	—	—	—	—	—	C	D
Perth	(PcP=D)	C	—	—	C	—	—	—	—	—	—	—	D	D (DD)	—
Philadelphia	—	—	—	—	—	—	—	—	—	—	—	—	—	C	—
Pietermaritzburg	—	—	—	C	—	—	—	D	—	—	D'_i	—	—	D	—
Pittsburgh	—	—	—	(D)	—	—	—	—	—	—	—	C	—	—	—
Prague	—	—	—	D	—	D'_i	—	(C)	—	—	D	—	D	(D)	—
Pretoria	—	—	—	—	—	—	—	D	—	D	(C'_i)	D'_i	—	(C)	—
Pulkovo	—	—	—	—	—	—	—	—	—	—	—	D	—	—	—
Punta Arenas	—	—	—	—	—	—	—	D	—	—	—	—	—	—	—
Quetta	D CC (PcP=C)	PcP=C	C'_i (cC'_i) DD	D	C (CC)	C'_i	D'_i	D'_i CC	D'_i	D (DD)	D	C	D (cC)	D	C'_i CC
Rapid City	—	—	—	—	—	—	—	—	—	—	—	—	—	(C)	(C)

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TABLE III—*Continued*

Data on which the Solutions are Based

STATION	Aug. 16, 1955	Aug. 21, 1955	Aug. 28, 1955	Sept. 12, 1955	Oct. 13, 1955	Nov. 10, 1955	Nov. 22, 1955	Jan. 8, 1956	Jan. 10, 1956	Jan. 31, 1956	Feb. 1, 1956	Feb. 9, 1956	Feb. 18, 1956	July 9A, 1956	July 9B, 1956
Rathfarnham	(D_i') dD_i' CC DDD	(D_i') (CC)	(D)	D	C_i' (CC)	D_i'	—	D (dD) (CC)	(C_i')	D_i'	D	C DD	D (dD) (CC)	C	D
Reggio Calabria	—	—	—	(C)	—	—	—	—	—	—	—	—	—	(D)	—
Relizane	—	—	—	D	—	—	—	—	—	—	—	—	—	—	D
Reno	D	—	C	—	C	—	D	C	—	D	D	D	C	—	—
Resolute	—	C	C	(D)	(D)	D (DD)	—	—	—	D	D	D	C	D	(D)
Reykjavik	C_i'	—	C dD	D	C_i'	D_i'	—	D	—	D_i'	D	—	C	(D)	(C)
Riverside	—	—	C	—	C	—	—	—	—	—	—	D	—	—	—
Riverview	(D) (cC)	(C) cC	—	(D_i') (cC_i') DD CCC	C (cC)	C cC	D	DD	CC	D dD	D (dD)	C_i'	D dD (CC) (DDD) PcP=D	(C_i') CC	—
Rome	—	—	—	D	C_i'	D_i'	—	(C)	D_i'	—	—	—	—	C	D (cC)
Saga	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Saint Louis	(D_i') CC DDD	C_i' (DD)	D (CCC)	(D) (cC) (DD) cCC	C DD	(C) CC	D	C cC	CC	D_i' CC	D CC	(D)	C (dD) DD	C (CC)	(C)
Salo	—	—	—	(C)	—	(C_i')	—	—	—	—	—	—	—	—	—
Salt Lake City	D	C	C	(D)	C	D	D	C	C	D	D	C	C	(C)	D
San Juan	—	C_i'	—	C	C_i'	—	D	D	—	—	(C_i')	(C)	—	C	D
Santa Clara	dD	—	C	—	C	D	—	(D)	—	—	—	—	C	D	D
Santa Lucia	—	—	—	—	—	C	—	(C)	—	—	—	—	—	—	—
Sapporo	D	D	—	—	C	(C)	—	—	—	—	D	—	C	—	—
Scoresby Sund	—	—	(D) (DD)	—	—	—	—	(C)	—	—	(C) (dD)	(C)	—	(D)	(C)
Seattle	D	C CC	C	—	C	D (PcP=C)	C	C DD	—	D	D	(C)	C (CC)	D	D
Semipalatinsk	D	C	—	C	C	—	—	—	—	—	D	—	—	D	—
Sendai	—	—	—	—	—	—	—	—	—	—	D	—	C	—	—
Seven Falls	C_i'	—	—	C	C_i'	—	D	D	—	D_i'	—	C	—	C	D
Shasta	D	C	C	C	C	D	C	C	C	D	D	—	C cC	—	D
Shawinigan Falls	C_i'	—	—	—	—	—	(C)	D	—	—	—	(D)	(D) (dD)	C	D
Shillong	—	—	—	—	—	—	—	—	—	—	—	C_i'	—	—	—
Shimizu	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Shionomisaki	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—

Shizuoka	D	—	—	—	—	—	—	—	C	—	D	—	D	—	—
Simferopol	—	—	—	C	—	—	—	—	—	—	(C)	D	D	—	—
Sitka	—	—	—	—	—	—	—	—	—	—	—	—	—	D	(C)
Skalnate Pleso	C'_1	—	—	—	C'_1	(C'_1) dD'_1 (DD)	—	—	—	—	—	—	D	—	—
Skalstugan	—	—	—	—	—	—	—	—	—	—	—	—	C (dD)	(D)	D (DD)
Spring Hill	—	—	—	—	—	—	D	—	—	—	—	—	—	—	—
Stara Dala	—	DD	—	—	—	dD'_1 (DD)	—	DD CCC (C)	—	—	—	—	D	—	—
State College	—	—	D (PcP=D)	—	—	—	—	—	—	—	—	—	(C'_1)	C	D
Strasbourg	C'_1 (cC'_1) CC (dDD)	—	C (cC) CC CCC	D	C'_1 (CC)	D'_1, dD'_1 CC	(D'_1)	D	(CC)	(C'_1)	D (DD)	D	D (dD) (dDD)	C	D
Stuttgart	C'_1	—	—	D (PcP=D)	—	D'_1	—	D	—	D'_1	D (DD)	(PcP=D)	(C) cC DD	C	D
Sumoto	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Suttsu	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Sverdlovsk	—	—	—	—	—	—	—	—	—	—	—	D	—	—	—
Tacubaya	(D'_1) (DD)	CC	D	—	DD	CC	—	C	D	—	—	(C)	—	(CC)	(D)
Takamatsu	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Tamanrasset	—	—	—	D	C'_1	(C'_2) dD'_2, C_1	—	D	—	D'_1	CC	—	—	D	D
Tananarive	(D)	—	—	(D)	—		—	—	—	(DD)	(C)	—	(C)	—	C'_1
Tashkent	D (cC) (DD)	C	C'_1	D	C	(C'_1)	—	(C'_1) CC	D'_1	D cC	D (CCC)	—	D	—	—
Tbilisi	D (DD)	(CC)	C CC	D	DD	D'_1	—	DD	D CC	D'_1	D cC (DD)	—	D	—	—
Tinemaha	—	—	—	—	C	—	D	—	—	—	—	D	—	—	—
Tokushima	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Tokyo	—	—	—	C	C	—	—	—	—	—	D	—	(C)	—	—
Toledo	—	—	—	—	C'_1	D'_1	—	D	—	—	—	—	—	—	D
Tomie	—	—	—	—	—	—	—	—	—	—	D	—	C	—	—
Tomizaki	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Tori-shima	—	—	—	—	—	—	—	—	—	—	D	—	D	—	—
Tortosa	—	—	—	—	—	—	—	—	—	—	—	D	—	—	—
Trieste	—	—	C	—	C'_1 (CC)	D'_1	—	—	—	—	—	—	—	C	—
Tuai	(D)	C	—	—	C	—	—	—	C	—	(C)	—	D	—	—
Tucson	D	—	D	—	C	D	D	C	—	D	D	C	D	D	D
Uccle	—	—	C	D	—	—	—	—	—	—	—	—	—	C	D
Ukiah	—	—	—	—	—	—	—	—	—	—	—	—	—	D	D
Uppsala	(DD)	DD	C dD	—	—	D'_1 dD'_1	—	—	—	D'_1	D	D	C (dD)	C	D CC
Urakawa	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Utsunomiya	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—

TABLE III—*Concluded*

Data on which the Solutions are Based

Station	Aug. 16, 1955	Aug. 21, 1955	Aug. 28, 1955	Sept. 12, 1955	Oct. 13, 1955	Nov. 10, 1955	Nov. 22, 1955	Jan. 8, 1956	Jan. 10, 1956	Jan. 31, 1956	Feb. 1, 1956	Feb. 9, 1956	Feb. 18, 1956	July 9A, 1956	July 9B, 1956
Uvira	—	—	—	—	—	—	—	—	—	D'_i	—	C'_i	D	—	C CC
Uwajima	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Vera Cruz	—	(DD)	D	—	—	(C)	—	C	—	—	—	—	—	—	—
Victoria	—	—	(D)	(D)	C	D	C	C	—	D	D cC	D	C (dD)	—	D
Vienna	—	—	—	D	—	D'_i	—	—	—	—	—	—	—	C	—
Warsaw	—	—	—	—	—	—	—	—	—	—	—	—	—	C	D
Washington	—	—	—	C	C'_i	—	—	D	—	—	—	(D)	—	(D)	D
Wellington	C	(C)	—	—	C dD (CC)	C	D	C	D	D	D	—	D	—	—
Weston	C'_i	C'_i	C	C	C'_i	—	—	(C)	—	—	—	C	(D)	(D)	D
Witteveen	—	—	—	—	—	—	—	—	—	—	—	—	—	C	D
Woody	D	D	—	—	C	—	D	—	—	—	—	D	—	—	—
Yaku-shima	—	—	—	—	—	—	—	—	—	—	—	—	D	—	—
Yokohama	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Zagreb	—	—	—	D	—	—	—	—	—	—	—	—	—	C	—
Zurich	C'_i	—	—	D	—	—	—	—	—	—	—	—	—	—	—

ANALYSIS OF THE DATA

The 15 solutions are treated individually in this section. A solution diagram showing a representative group of stations, a short discussion, and a table summarizing the inconsistencies for all phases are given in each case. Although reflected phases occur in the tables, it should be stressed that they did in no way influence the solutions; rather the solutions were used to test the accuracy of the reflected phases.

Earthquake of 11:46:58, Aug. 16, 1955. $\varphi = 6°S, \lambda = 155°E$

The solution for this earthquake is shown in Figure 1, and the score for the solution is given in Table IV. The score for the direct phases is poorer than usual. This is chiefly

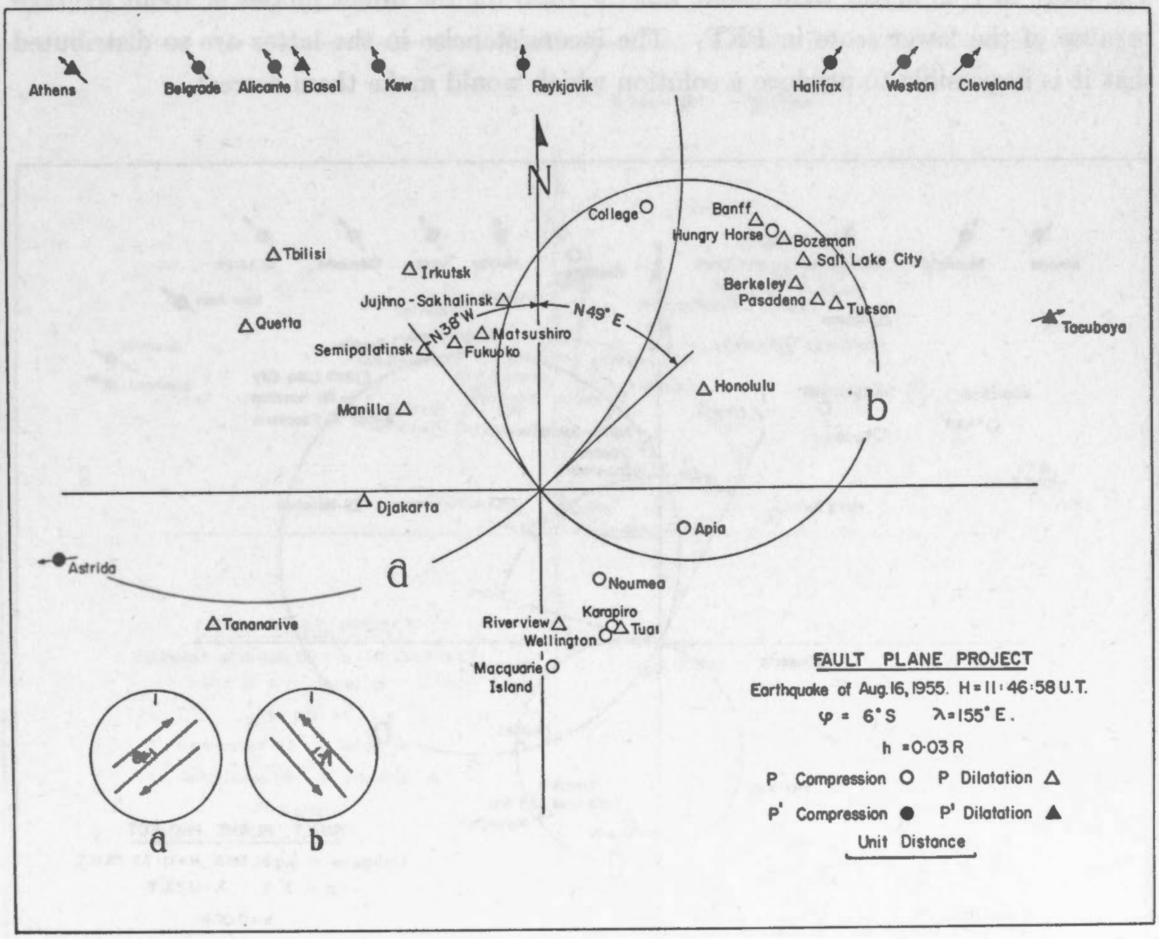

Figure 1

due to the large number of inconsistent observations of PKP. However these inconsistent observations of PKP are surrounded in most instances by consistent observations and do not introduce serious doubt about the solution.

TABLE IV

	Direct Phases			Reflected Phases						
	P	P'_1	Total	PP	pP	pP'_1	PPP	pPP	PcP	Total
Total Number of Observations......	49	35	84	24	7	8	3	5	2	49
Number of Inconsistent Observations	8	11	19	12	4	5	1	4	2	28

Earthquake of 17:33:58, Aug. 21, 1955. $\varphi = 3°S$, $\lambda = 137\frac{1}{2}°E$

Figure 2 gives the solution for this earthquake. The score is shown in Table V. The score in P is better than usual, but the total for the direct phases is about average because of the lower score in PKP. The inconsistencies in the latter are so distributed that it is impossible to produce a solution which would make them correct.

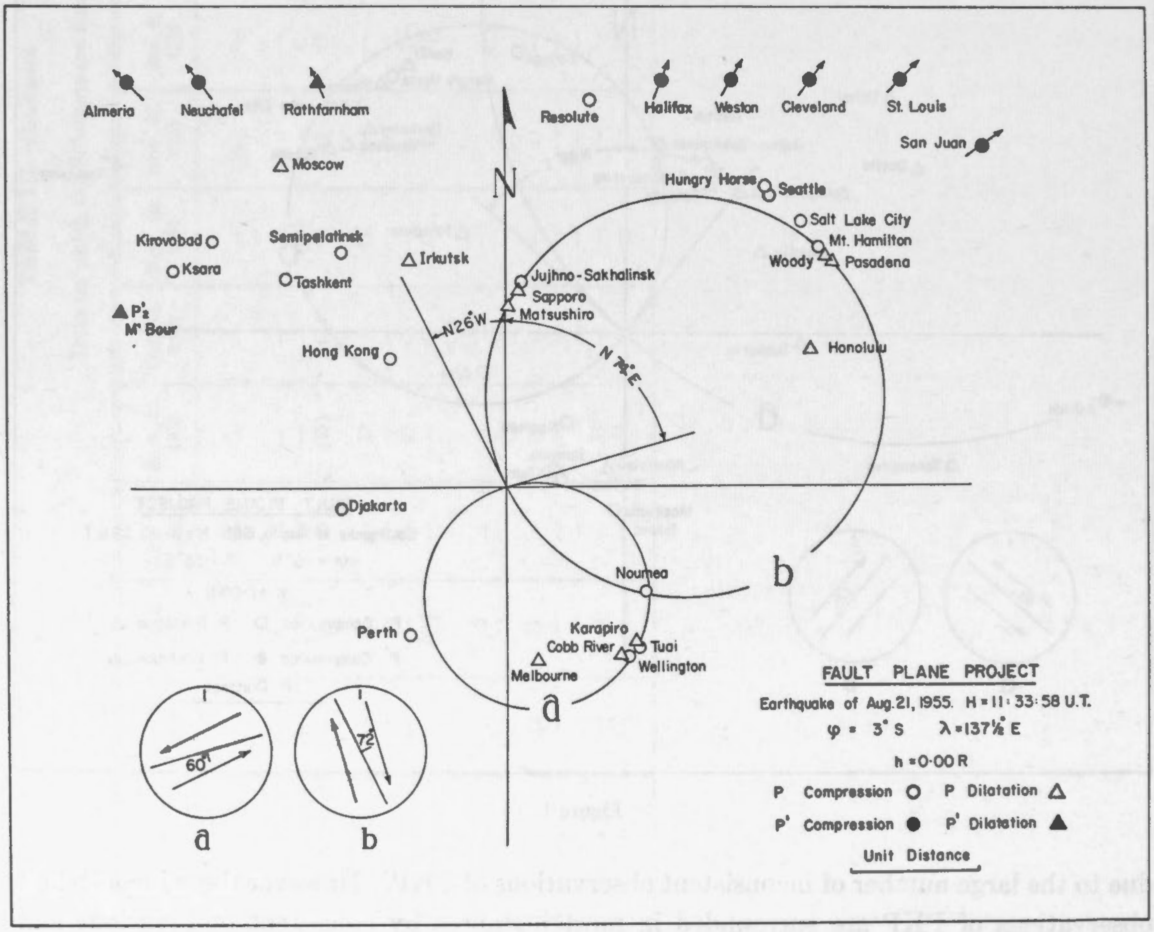

Figure 2

TABLE V

	Direct Phases				Reflected Phases					
	P	P'_1	P'_2	Total	PP	pP	PPP	pPP	PcP	Total
Total Number of Observations......	33	19	1	53	21	1	2	1	1	28
Number of Inconsistent Observations	4	4	1	9	9	0	1	0	0	10

Earthquake of 20:13:30, Aug. 28, 1955. $\varphi = 14°N$, $\lambda = 91°W$

The solution for this earthquake is shown in Figure 3. As shown in Table VI there is a very high percentage of inconsistencies in P. These derive largely from European

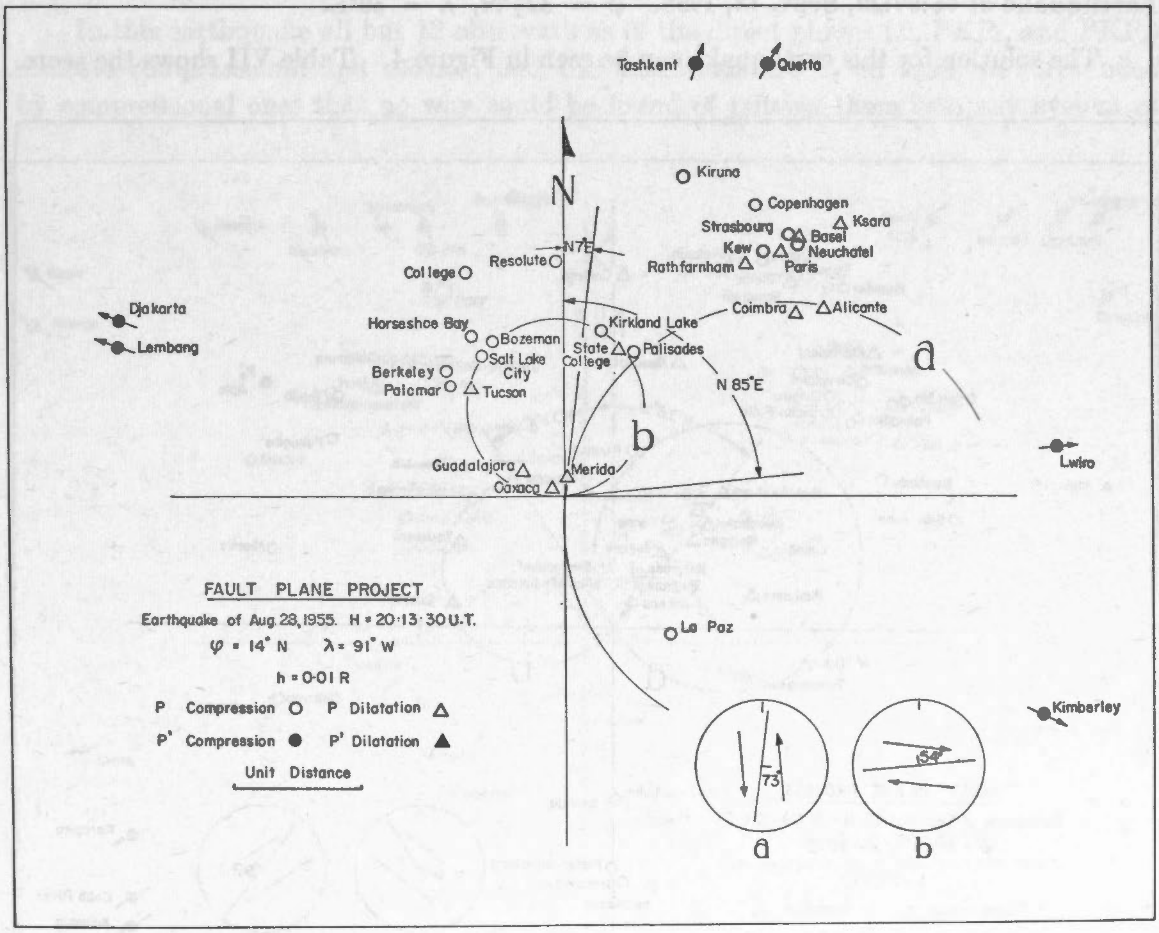

Figure 3

stations and reflect the doubts about the exact position of circle *a*. Rathfarnham, Paris, Basel and Ksara, for example report clear dilatations, but if circle *a* is increased in radius to include them, it makes inconsistent Kew and Palisades and a number of other stations not shown. The indicated solution is the best statistically; in any event the required variation would not be geologically large.

TABLE VI

	Direct Phases			Reflected Phases						
	P	P_1'	Total	PP	pP	pP_1'	PPP	pPP	PcP	Total
Total Number of Observations......	68	8	76	13	5	2	4	1	2	27
Number of Inconsistent Observations	18	0	18	4	3	2	1	1	2	13

Earthquake of 06:09:20, Sept. 12, 1955. $\varphi = 32\frac{1}{2}°N$, $\lambda = 30°E$.

The solution for this earthquake can be seen in Figure 4. Table VII shows the score.

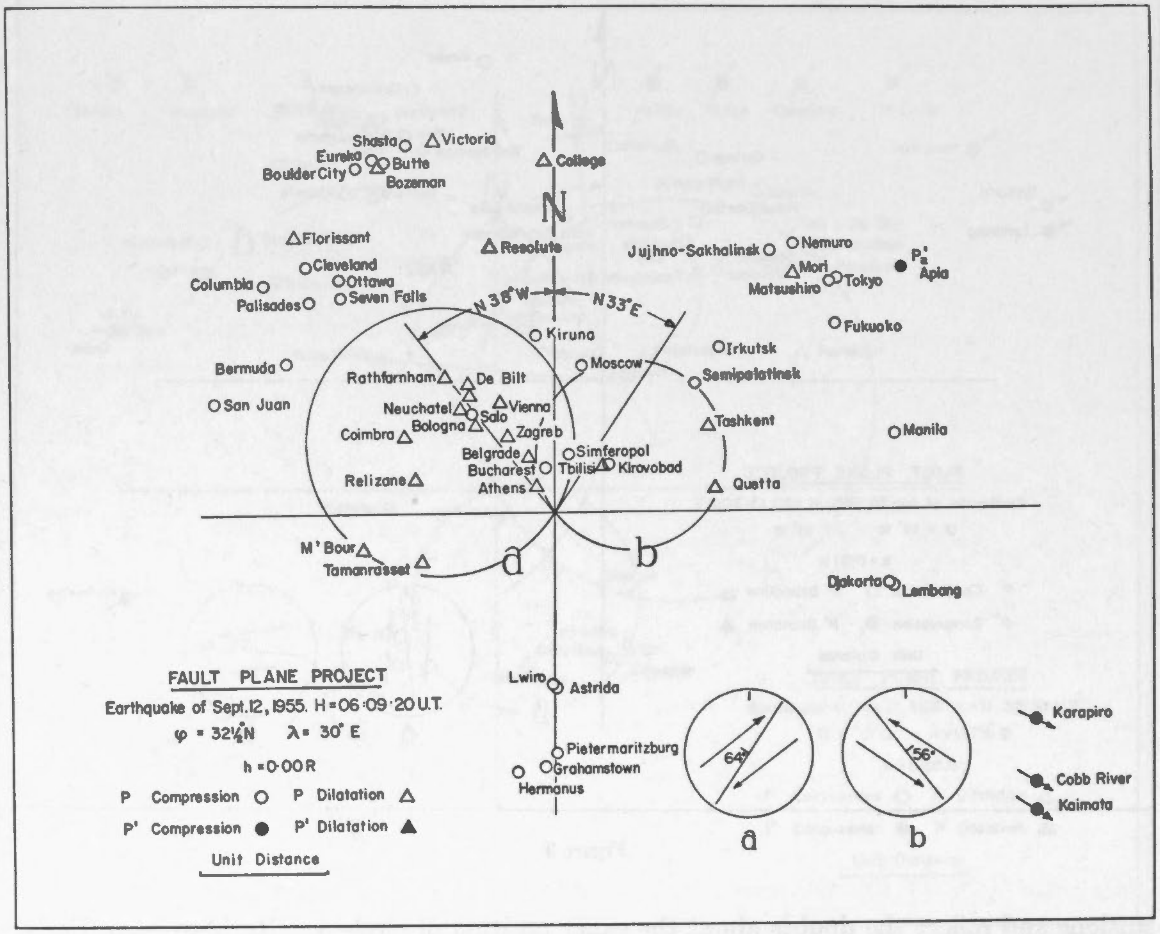

Figure 4

Nearly all the inconsistencies in P are contained well within areas of consistent data and thus cannot be brought into the solution. While the large number of inconsistencies is disturbing, it does not cast serious doubt on the solution.

TABLE VII

	Direct Phases				Reflected Phases						
	P	P_1'	P_2'	Total	PP	pP	pP_1'	PPP	pPP	PcP	Total
Total Number of Observations.......	90	4	1	95	4	3	1	2	1	2	13
Number of Inconsistent Observations.	19	1	0	20	2	3	1	0	0	1	7

Earthquake of 09:26:44, Oct. 13, 1955. $\varphi = 9\frac{1}{2}°S$, $\lambda = 161°E$.

In this earthquake all but 12 observations of the direct phases (P, PKP_1, and PKP_2) indicate compressional first motion, and the dilatations are in all cases so surrounded by compressional ones that no way could be found of putting them into any system of

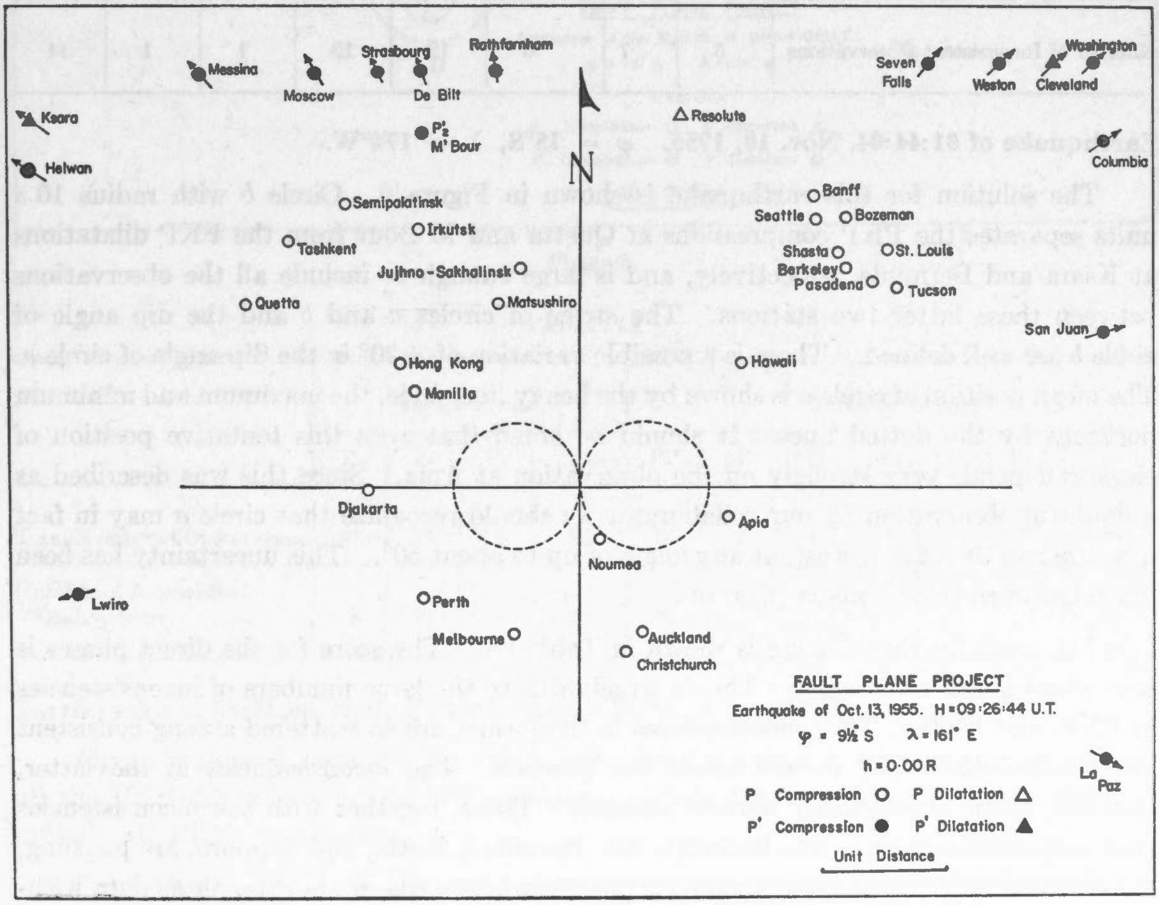

Figure 5

circles. It was necessary to conclude that all the observations should have been compressional, and that the solution would consist of a pair of dilatational circles drawn in the area, close to the epicentre, which was free of observation. This could have been done in an infinity of ways. The diagram (Figure 5) shows one possible set, a pair of planes striking N and each dipping at 45°, but a circle representing a plane dipping as much as 63° could have been drawn in the free area.

In drawing a second circle however we would have been limited to circles having approximately the same strike direction; from this we may conclude that faulting is probably thrust, on a fault having an unknown strike and dip.

We regard this as a solution in the sense that the observations have been satisfactorily accounted for. The score for the solution is given in Table VIII.

TABLE VIII

	Direct Phases				Reflected Phases			
	P	P_1'	P_2'	Total	PP	pP	PPP	Total
Total Number of Observations.......	63	37	3	103	19	3	2	24
Number of Inconsistent Observations.	5	7	0	12	12	1	1	14

Earthquake of 01:44:04, Nov. 10, 1955. $\varphi = 15°S$, $\lambda = 174°W$.

The solution for this earthquake is shown in Figure 6. Circle *b* with radius 10.3 units separates the PKP compressions at Quetta and M'Bour from the PKP dilatations at Ksara and Bermuda respectively, and is large enough to include all the observations between these latter two stations. The strike of circles *a* and *b* and the dip angle of circle *b* are well defined. There is a possible variation of $\pm 20°$ in the dip angle of circle *a*. The mean position of circle *a* is shown by the heavy line circle, the maximum and minimum positions by the dotted lines. It should be noted that even this tentative position of circle *a* depends very strongly on the observation at Apia. Since this was described as a doubtful observation by our collaborator we should recognize that circle *a* may in fact dip either to the east or west, at any angle of up to about 50°. This uncertainty has been indicated in the single insert diagram.

The score for the solution is shown in Table IX. The score for the direct phases is somewhat poorer than usual. This is largely due to the large numbers of inconsistencies in PKP_1 and PKP_2. The inconsistencies in the former are so scattered among consistent observations that they do not affect the solution. The inconsistencies in the latter, however, occur in one fairly narrow azimuth. These, together with the inconsistencies from dependable stations like Berkeley, Mt. Hamilton, Butte, and Sapporo, are puzzling, yet it is impossible to find a solution which will satisfactorily account for these data without producing a much poorer score in the P observation.

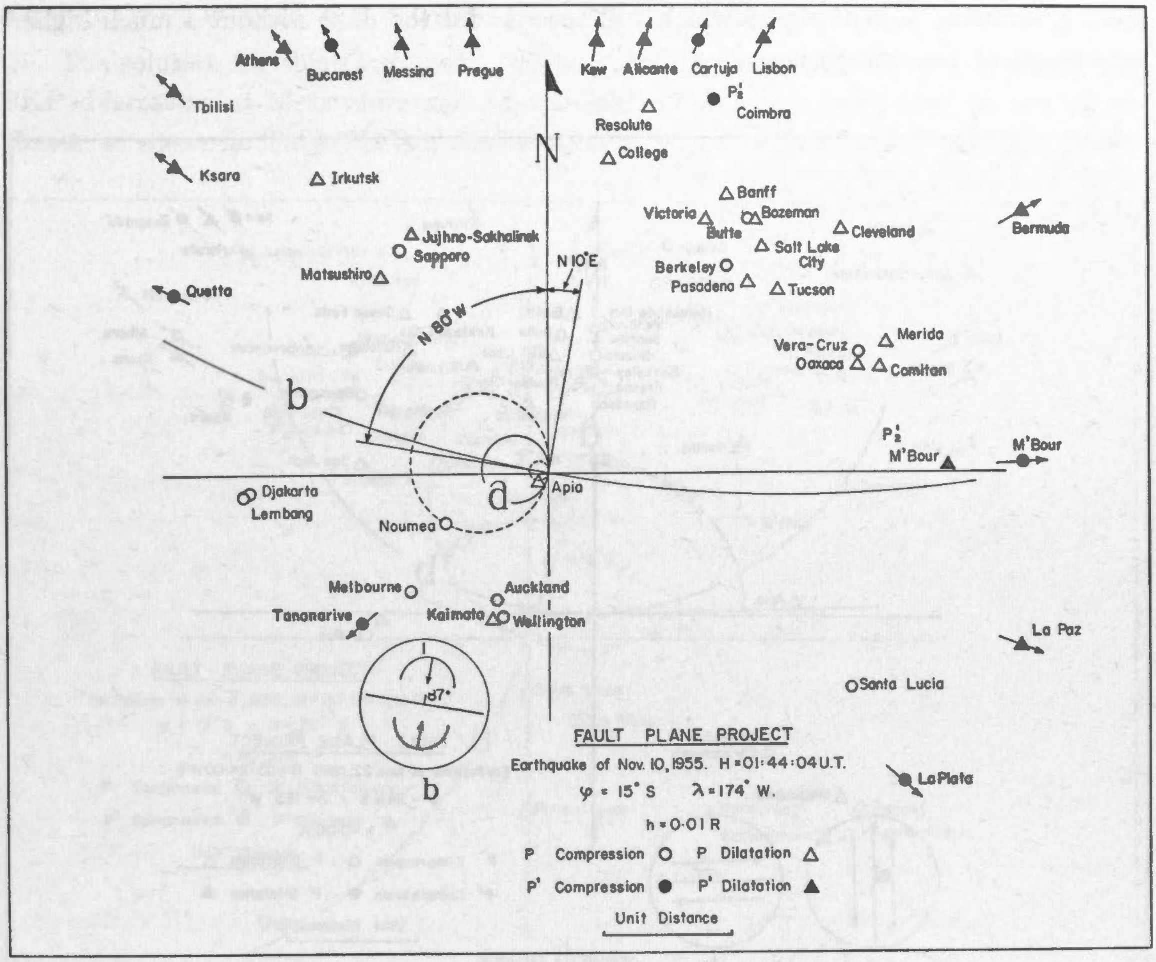

Figure 6

TABLE IX

	Direct Phases				Reflected Phases						
	P	P'_1	P'_2	Total	PP	pP	pP'_1	pP'_2	pPP	PcP	Total
Total Number of Observations	42	42	5	89	16	2	8	1	1	1	29
Number of Inconsistent Observations............	8	10	4	22	11	1	2	0	0	1	15

Earthquake of 03:24:00, Nov. 22, 1955. $\varphi = 24\frac{1}{2}°S$, $\lambda = 123°W$.

Figure 7 gives the solution for this earthquake. Circle *a* is large enough to include all the PKP dilatations in the NW quadrant. Circle *b* has sufficiently small radius to exclude all PKP observations.

From Table X it can be seen that the number of inconsistencies in the direct phases is rather high. Nevertheless the solution is submitted with some confidence because there is no other pair of circles which will account for the data without a much higher percentage of inconsistencies.

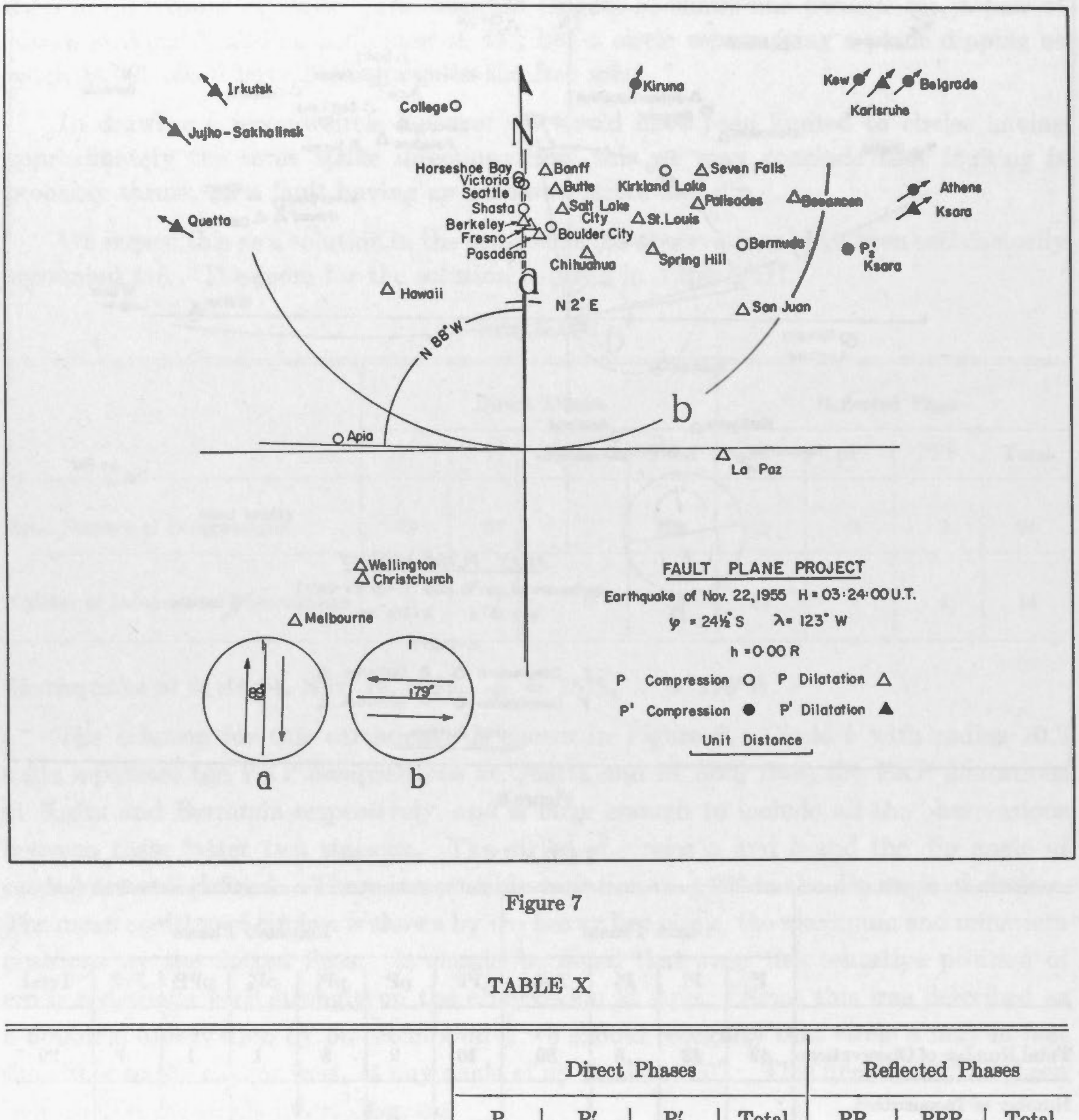

Figure 7

TABLE X

	Direct Phases				Reflected Phases		
	P	P'_1	P'_2	Total	PP	PPP	Total
Total Number of Observations	41	13	1	55	3	1	4
Number of Inconsistent Observations	10	4	0	14	1	0	1

This is the first earthquake in this geographic area—the Eastern Tuamota Archipelago—for which a fault-plane solution has been obtained.

Earthquake of 20:54:13, Jan. 8, 1956. $\varphi = 19°S$, $\lambda = 70°W$.

The solution for this earthquake will be found in Figure 8. Circle *a* excludes the PKP dilatations at Matsushiro and Jujhno-Sakhalinsk. The poor score in the direct phases, as shown in Table XI is a combination of poor scores in both P and P_1'. Since

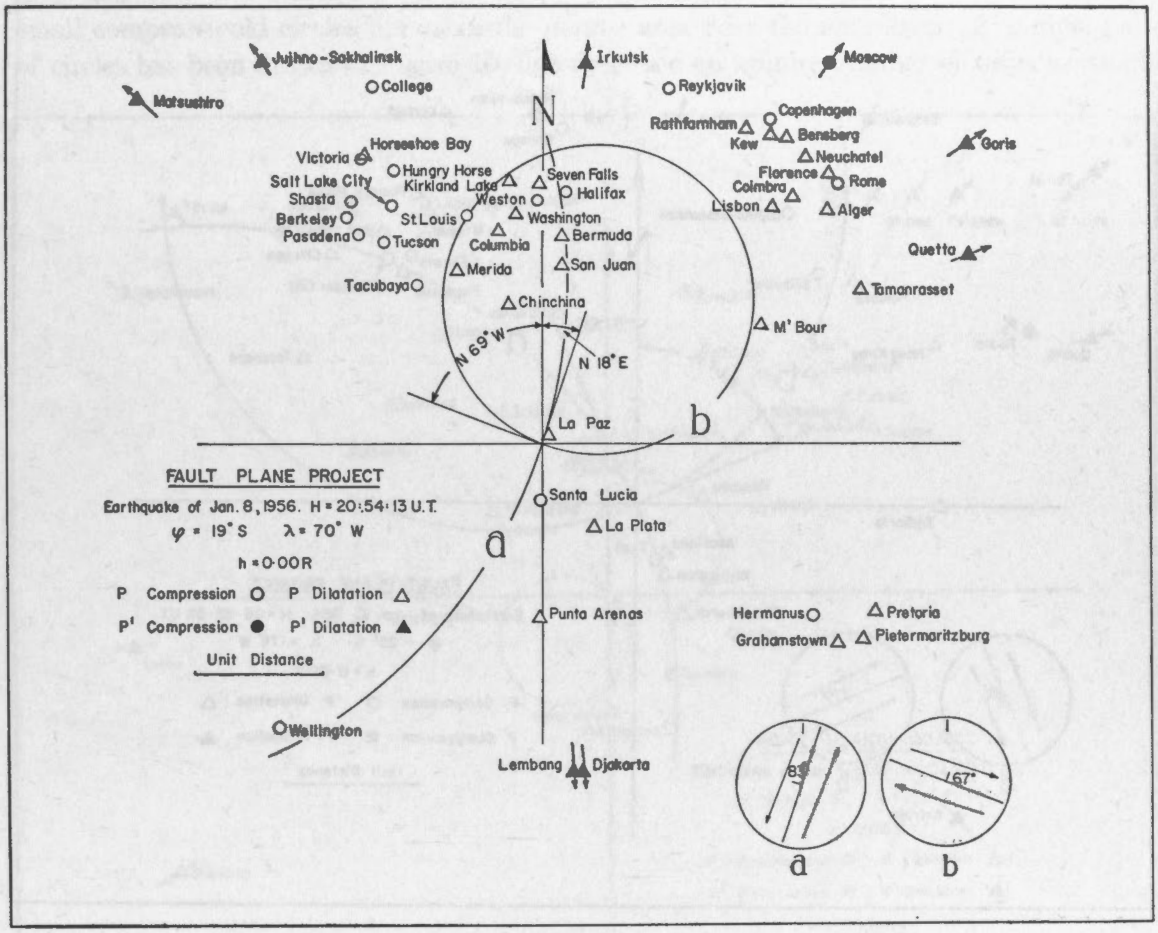

Figure 8

the corresponding inconsistencies are distributed at randon among consistent observations, they do not cast any doubt on the final solution.

TABLE XI

	Direct Phases			Reflected Phases				
	P	P_1'	Total	PP	pP	PPP	pPP	Total
Total Number of Observations......	78	11	89	17	3	3	1	24
Number of Inconsistent Observations.	17	4	21	6	2	0	0	8

Earthquake of 08:52:36, Jan. 10, 1956. φ = 25°S, λ = 176°W.

As shown in Table XII there are fewer observations than usual for this earthquake but, except for the large number of inconsistencies in P'_2 the percentage of inconsistencies is satisfactory. Circle *a* (Figure 9) has remarkable success in separating Tuai from the rest of the New Zealand stations, and Pasadena from the rest of the California ones, and is very closely defined. Circle *b* is not so closely defined, but has been drawn in the mean position to separate Fukuoko and Shizuoko.

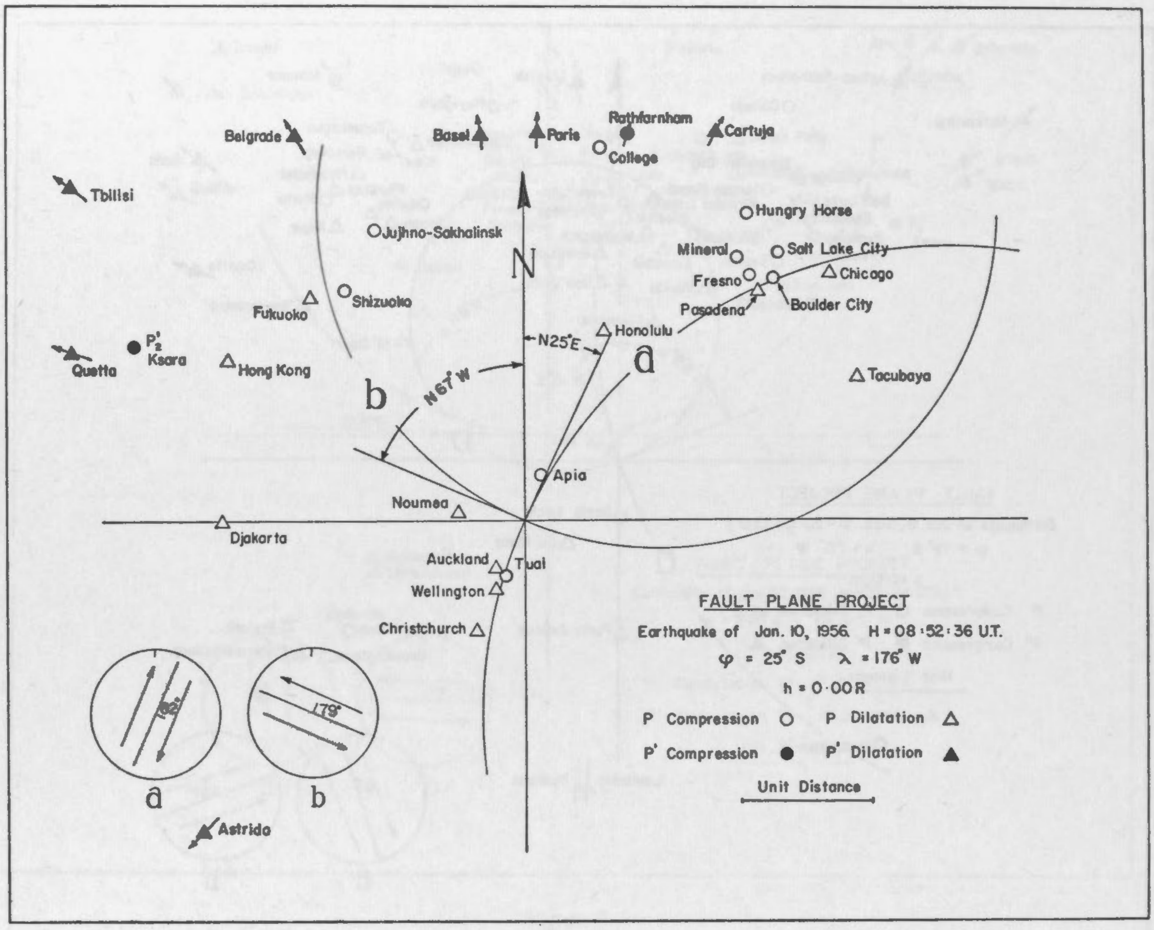

Figure 9

TABLE XII

	Direct Phases				Reflected Phases	
	P	P'_1	P'_2	Total	PP	Total
Total Number of Observations	30	17	4	51	11	11
Number of Inconsistent Observations	3	3	4	10	4	4

Earthquake of 09:17:11, Jan. 31, 1956. $\varphi = 4°S$, $\lambda = 152°E$.

This earthquake like that of Oct. 13, 1955, discussed earlier, and that of Feb. 1, 1956 to follow, is so located that the solution circles cannot be defined, even though the observations are well accounted for. In the present case all but 6 of 66 observations of P and PKP are dilatational, and the only possible solution is provided by a pair of small compressional circles drawn in the empty area near the epicentre. A sample pair of circles has been drawn in Figure 10, but there are an infinite number of ways in which

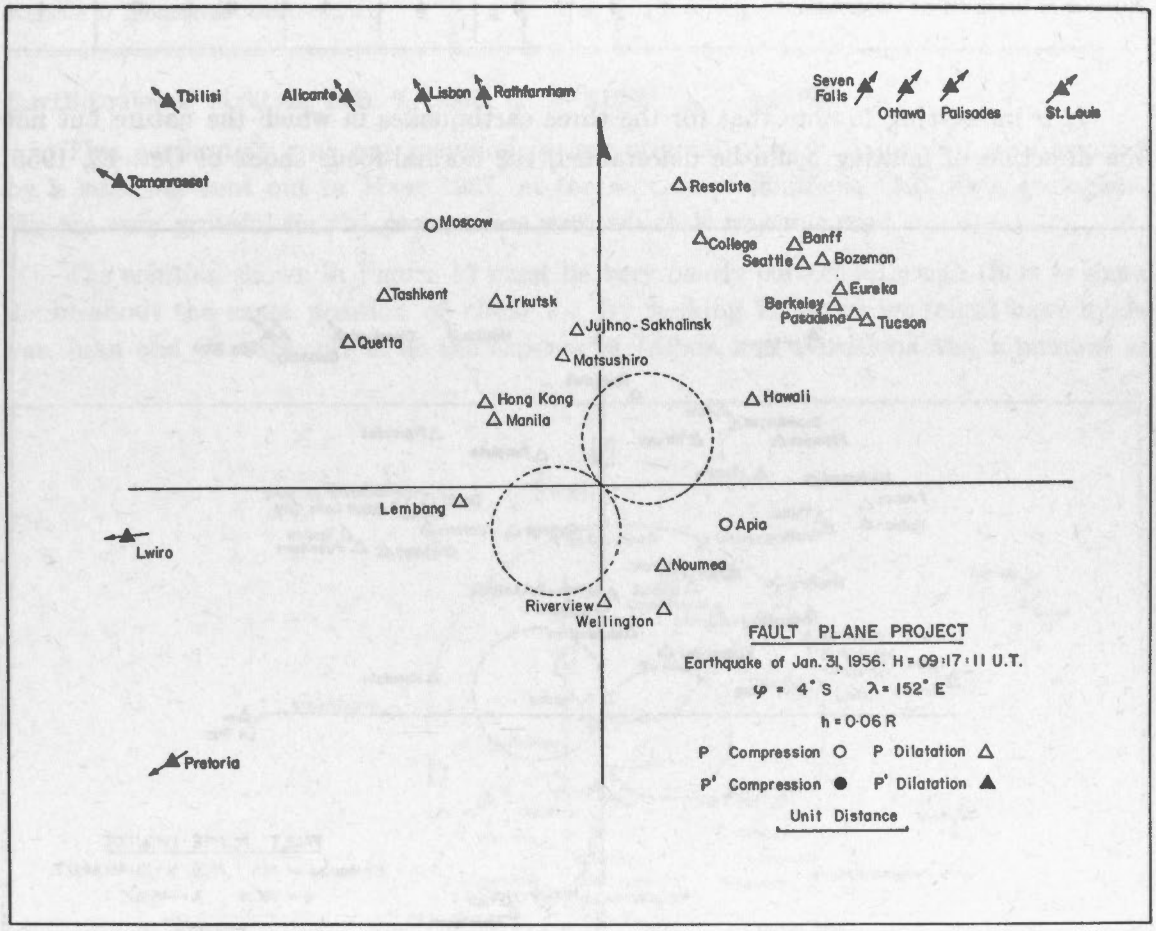

Figure 10

this could have been done. We may conclude that faulting is normal on a fault of indeterminate strike and dip. The circles could easily be drawn in such a way as to make Apia consistent; this has not been done because the observation was described as uncertain. The score is given in Table XIII.

Earthquake of 13:41:44, Feb. 1, 1956. $\varphi = 19°N$, $\lambda = 145\frac{1}{2}°E$.

Again we present an earthquake (*see* Figure 11) in which the solution cannot be defined because of the scarcity of stations close to the epicentre, but in which it is possible to conclude that the faulting is normal along a plane of indeterminate strike and dip. The score given in Table XIV is very good in the direct phases.

TABLE XIII

	Direct Phases			Reflected Phases			
	P	P_1'	Total	PP	pP	PPP	Total
Total Number of Observations..............	40	26	66	6	3	1	10
Number of Inconsistent Observations.........	1	3	4	4	0	0	4

It is interesting to note that for the three earthquakes in which the nature but not the direction of faulting could be determined, the normal-focus shock of Oct. 13, 1955,

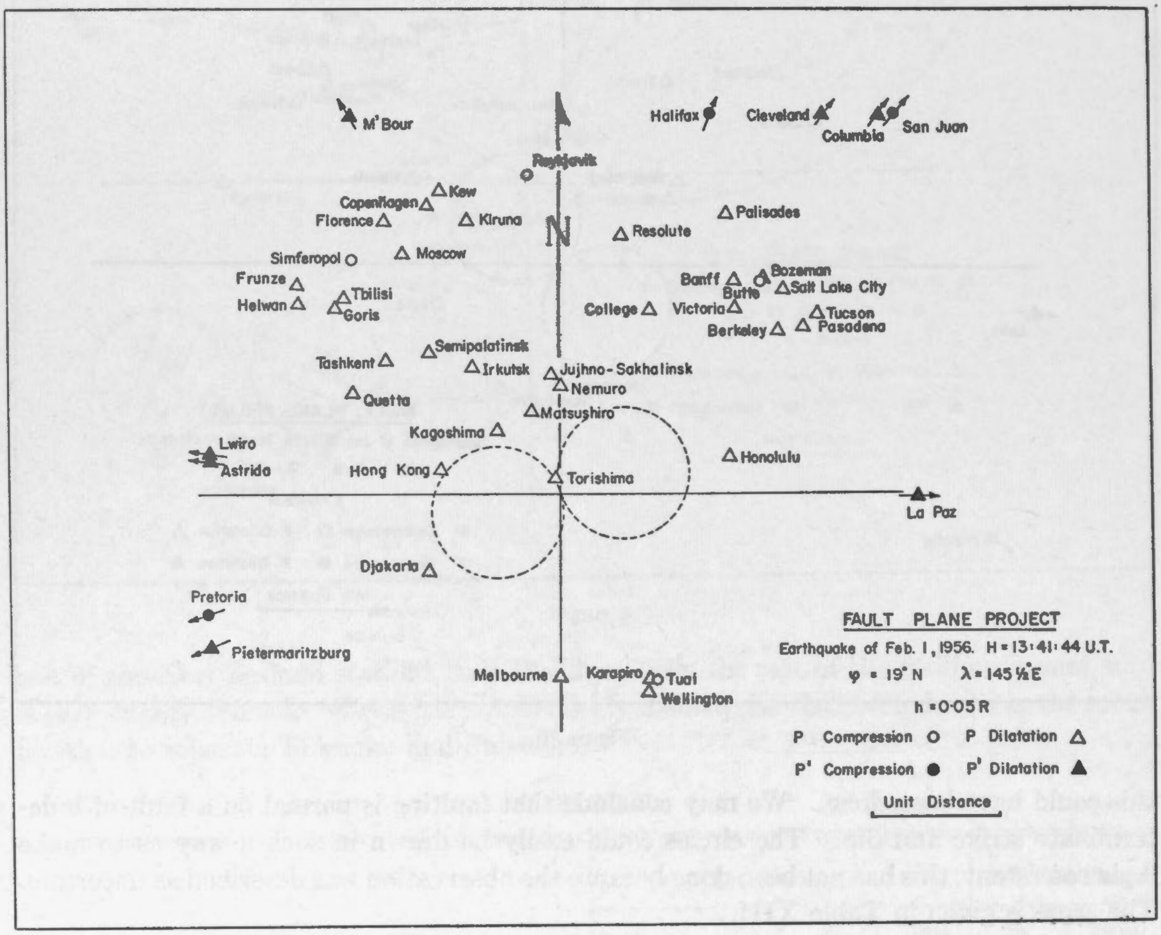

Figure 11

showed thrust faulting, while the deep-focus earthquakes of Jan. 31, 1956 and Feb. 1, 1956, showed tension faulting. This is what would have been expected on the contraction hypothesis.

TABLE XIV

	Direct Phases			Reflected Phases						
	P	P$'_1$	Total	PP	pP	pP$'_1$	PPP	pPP	PcP	Total
Total Number of Observations......	117	14	131	20	12	1	5	1	1	40
Number of Inconsistent Observations	9	6	15	12	7	1	5	1	1	27

Earthquake of 14:32:40, Feb. 9, 1956. $\varphi = 31\frac{1}{2}°N, \lambda = 116°W.$

This earthquake was not included in our original questionnaire, but was covered by a later one sent out in May, 1957, at the request of Southern California geologists. We are very grateful for the promptness with which it was returned.

The solution shown in Figure 12 must be very nearly correct although there is some doubt about the exact position of circle *b*. By making it larger we might have made San Juan and Cartuja correct at the expense of Lisbon and Barcelona and a number of

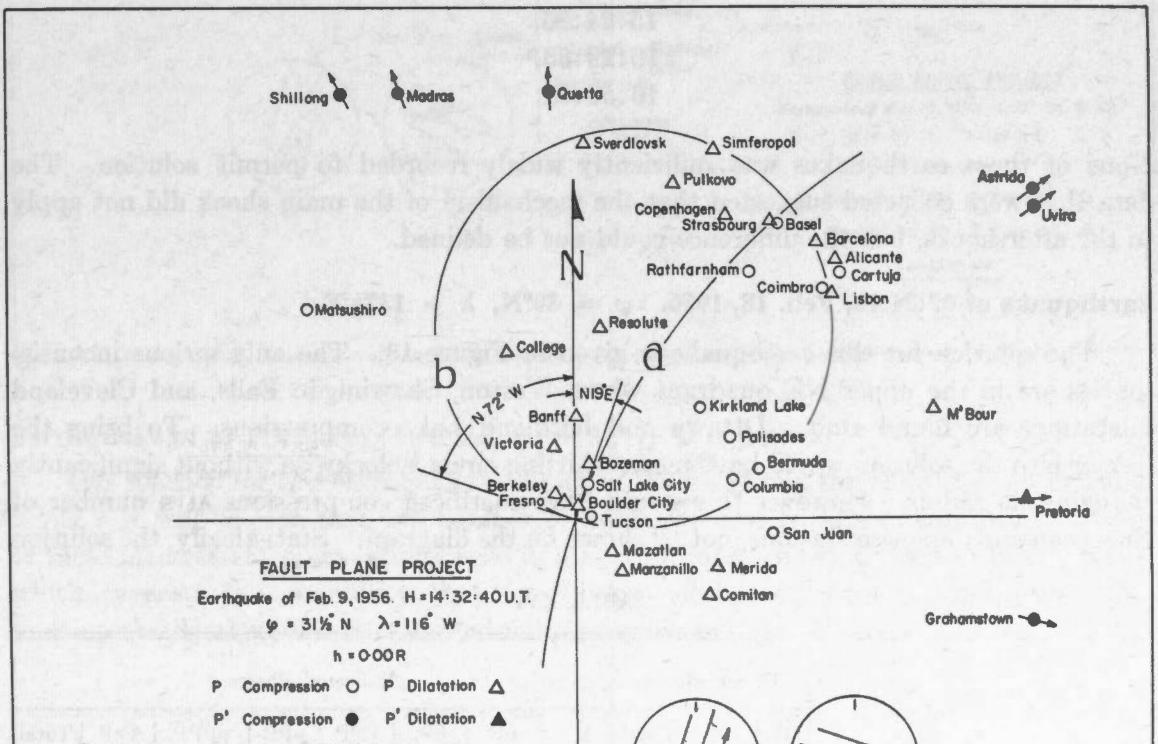

Figure 12

other stations not given in the diagram. The adopted position gives the best score, but the uncertainty is reflected in the high percentage of inconsistencies in P as shown in Table XV.

TABLE XV

	Direct Phases			Reflected Phases			
	P	P'_1	Total	PP	PPP	PcP	Total
Total Number of Observations...............	82	9	91	4	2	1	7
Number of Inconsistent Observations.........	15	2	17	2	0	1	3

No description of the observed faulting has yet been published, but we are advised by Dr. Clarence R. Allen* that "tentatively, plane *b* corresponds very nicely with the observed break and with the line of aftershock epicentres".

The same questionnaire sought information on principal aftershocks, with the following H times:

15:24:26,
16:29:53,
16:59:54.

None of these earthquakes was sufficiently widely recorded to permit solution. The data that were collected suggested that the mechanism of the main shock did not apply to the aftershocks, but the difference could not be defined.

Earthquake of 07:34:16, Feb. 18, 1956. $\varphi = 30°N$, $\lambda = 137\frac{1}{2}°E$.

The solution for this earthquake is given in Figure 13. The only serious inconsistencies are in the upper NE quadrant where Weston, Shawinigan Falls, and Cleveland dilatations are found among Ottawa and Kirkland Lake compressions. To bring the former into the solution would have meant shifting circle *b* clockwise without significantly changing its radius. However this would have sacrificed compressions at a number of European and Japanese stations, not all shown on the diagram. Statistically, the solution

TABLE XVI

	Direct Phases			Reflected Phases							
	P	P'_1	Total	PP	pP	pP'_1	PPP	pPP	pPPP	PcP	Total
Total Number of Observations....	105	5	110	19	23	1	5	2	1	2	53
Number of Inconsistent Observations.................	19	2	21	10	16	1	3	1	0	1	32

* Personal communication.

as given is much better and the score for the direct phases (*see* Table XVI) has about the usual value. Inconsistencies other than those mentioned are scattered throughout the diagram apparently at random and reflect no doubt on the solution.

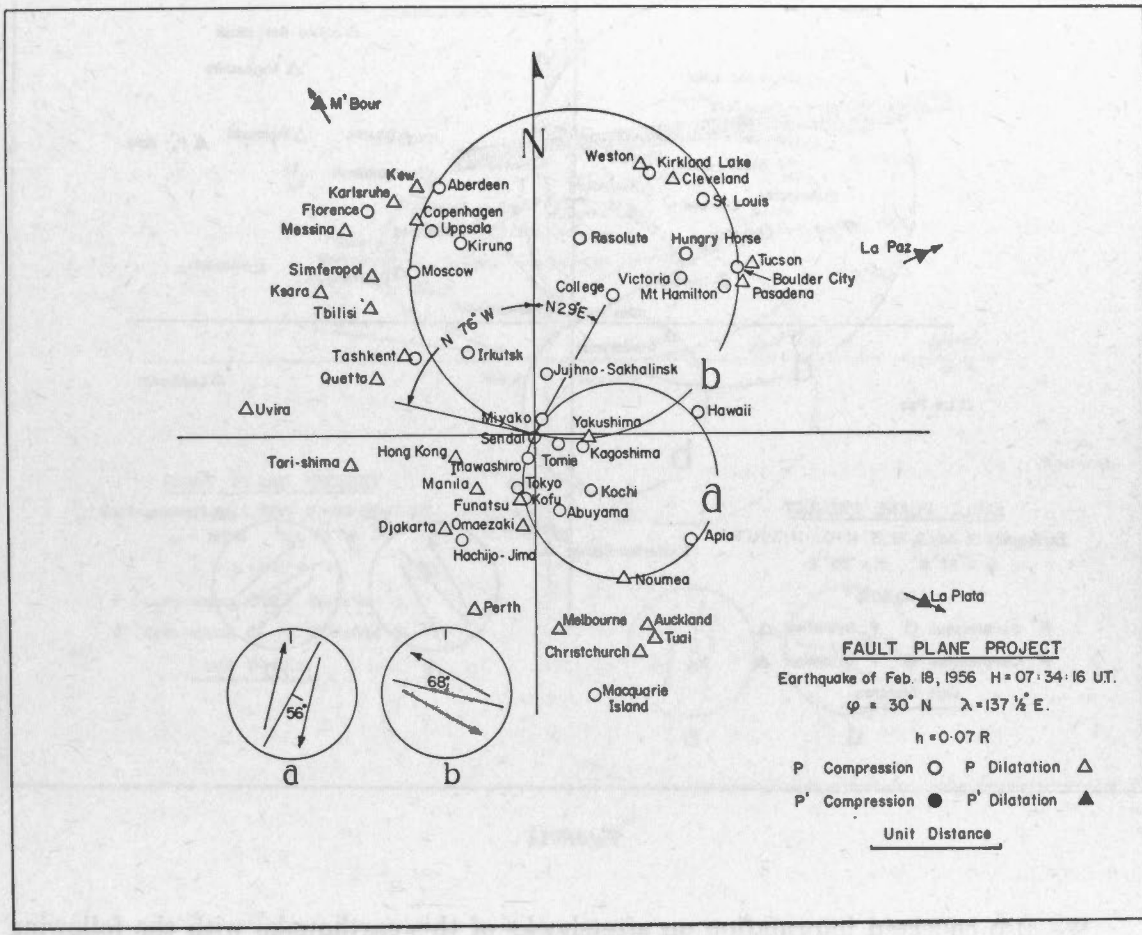

Figure 13

Earthquake of 03:11:39, July 9, 1956. $\varphi = 37°N$, $\lambda = 26°E$.

Our solution for this earthquake is shown in Figure 14 and the score is given in Table XVII. It will be seen that the number of inconsistencies is higher than usual. Many of these inconsistent observations arise in a narrow band, shown shaded in the diagram, which suggests the possibility that some other mechanism may be operating. The solution should therefore be regarded with some reservation.

TABLE XVII

	Direct Phases				Reflected Phases				
	P	P_1'	P_2'	Total	PP	pP	PPP	PcP	Total
Total Number of Observations............	96	1	1	98	9	1	2	2	14
Number of Inconsistent Observations.......	24	1	0	25	7	1	0	2	10

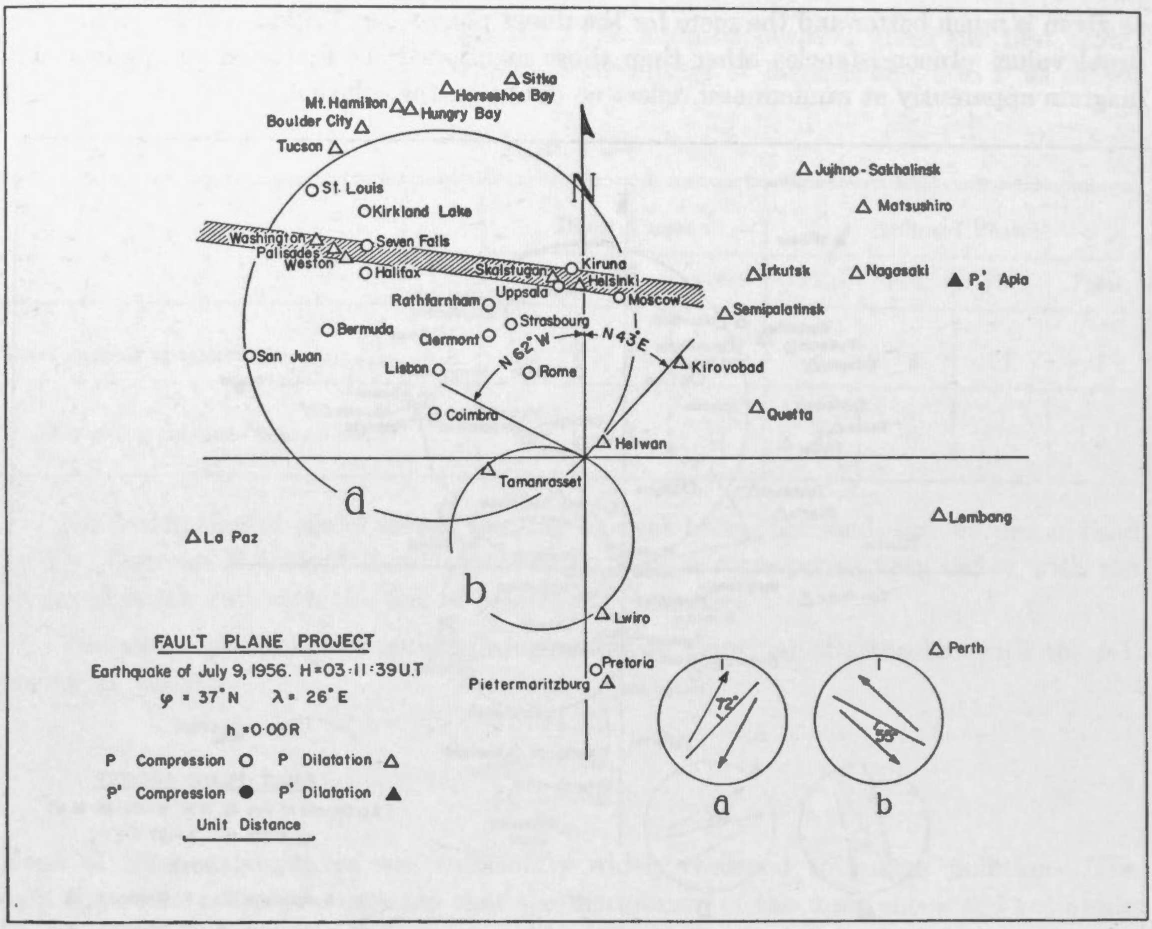

Figure 14

We also collected information on aftershocks of this earthquake with the following H times:

July 9, 1956, 03:24:05,
06:19:07,
06:22:49,
July 10, 1956, 03:01:27.

There were not sufficient data on any of these aftershocks to permit solutions.

Earthquake of 09:56:13, July 9, 1956. $\varphi = 20°N, \lambda = 73°W$.

The solution for this earthquake is shown in Figure 15, and the score is given in Table XVIII. The solution is straightforward except that both circles *a* and *b* have been drawn in mean positions from which they might deviate by about ±5°.

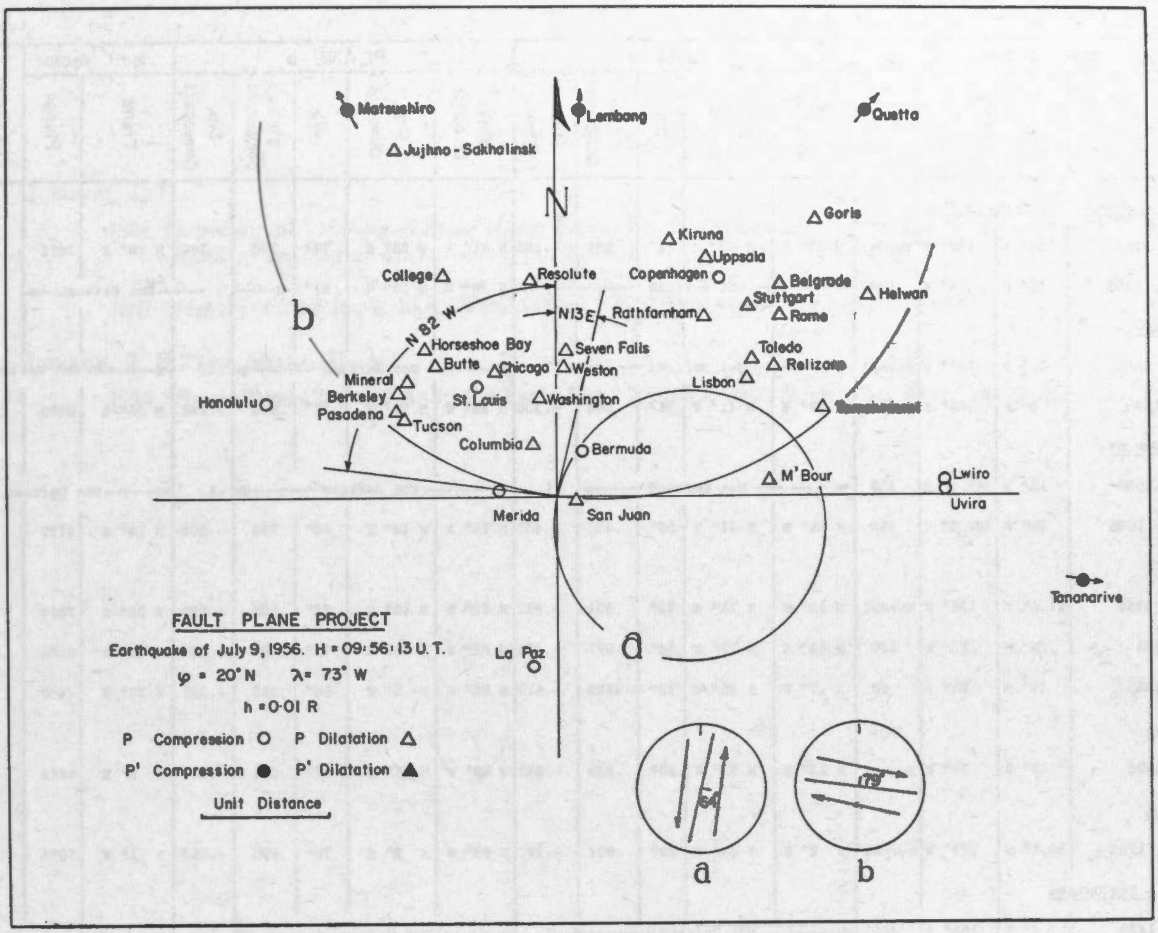

Figure 15

TABLE XVIII

	Direct Phases			Reflected Phases					
	P	P_1	Total	PP	pP	PPP	pPP	PcP	Total
Total Number of Observations...........	89	4	93	15	3	1	1	2	22
Number of Inconsistent Observations.......	14	0	14	7	1	1	1	1	11

SUMMARY

The solutions have been summarized in Table XIX, which is similar in form to the tables used in a recent review paper (Hodgson, 1957). Until more solutions have accumulated in this second series of solutions, no further discussion of the results is justified.

Table XIX

EARTHQUAKE				PLANE a					PLANE b					Null Vector		DEXTRAL Solution	SINISTRAL Solution
DATE	φ	λ	Focal Depth-km.	Strike Direction	Dip Direction	Dip	Strike Component	Dip Component	Strike Direction	Dip Direction	Dip	Strike Component	Dip Component	Trend	Plunge		
New Zealand - Kermadecs - Tonga - Fiji																	
January 10, 1956	25° S	176° W	Normal	N 25° E	S 65° E	82°	.981	-.193	N 67° W	N 23° E	79°	.990	-.142	N 60° E	76°.4	a	b
November 10, 1955	15° S	174° W	100	← Not Defined →					N 80° W	N 10° E	87°	←	+	Not Defined →		a	b
Solomon Islands																	
October 13, 1955	9.5 S	161° E	Normal	← Not Defined →				+1.	← Not Defined →				+1.	← Not Defined →			
August 16, 1955	6° S	155° E	200	N 49° E	N 41° W	81°	.944	+.330	N 38° W	N 52° E	71°	.986	+.166	N 26° E	68°.9	a	b
Marianas - Bonins																	
February 1, 1956	19° N	145.5° E	350	← Not Defined →				-1.	← Not Defined →				-1.	← Not Defined →			
February 18, 1956	30° N	137.5° E	450	N 29° E	S 61° E	56°	.892	-.452	N 76° W	N 14° E	68°	.798	-.603	N 78° E	47°.7	a	b
North America																	
February 9, 1956	31.5° N	116° W	Normal	N 19° E	S 71° E	85°	.951	+.311	N 72° W	N 18° E	72°	.996	+.092	N 35° E	70°.9	b	a
July 9 B, 1956	20° N	73° W	100	N 13° E	S 77° E	64°	.977	+.213	N 82° W	N 8° E	79°	.894	+.447	N 77° E	61°.6	b	a
August 28, 1955	14° N	91° W	60	N 7° E	S 83° E	73°	.789	+.615	N 85° E	N 5° W	54°	.932	+.361	N 27° E	48°.6	b	a
South America																	
January 8, 1956	19° S	70° W	Normal	N 18° E	N 72° W	83°	.919	-.393	N 69° W	N 21° E	67°	.991	-.132	N 2° E	65°.8	b	a
South Pacific																	
November 22, 1955	24.5° S	123° W	Normal	N 2° E	N 88° W	89°	.981	+.197	N 88° W	N 2° E	79°	.999	+.018	N 1° W	78°.5	a	b
New Britain - New Guinea																	
January 31, 1956	4° S	152° E	400	← Not Defined →				-1.	← Not Defined →				-1.	← Not Defined →			
August 21, 1955	3° S	137.5° E	Normal	N 74° E	S 16° E	60°	.934	+.357	N 26° W	N 64° E	72°	.851	+.526	S 53° E	54°.0	b	a
Mediterranean																	
September 12, 1955	32.5° N	30° E	Normal	N 33° E	N 57° W	64°	.783	+.623	N 38° W	N 52° E	56°	.849	+.529	N 4° E	44°.2	a	b
July 9 A, 1956	37° N	26° E	Normal	N 43° E	N 47° W	72°	.798	-.603	N 62° W	S 28° W	55°	.926	-.377	S 65° W	48°.1	a	b

It was mentioned in the introduction that the reflected phases would not be used in the solutions, but that solutions based on the direct phases alone would be used to test the reliability of the reflected phases. The results of this analysis have been given with each solution, but they are summarized in Table XX. It is clear once again that none of the reflected phases is reliable.

TABLE XX

Phase	PP	pP	pP′₁	pP′₂	pPP	PPP	pPPP	PcP
Number of Observations	201	66	21	1	14	33	1	16
Number of Inconsistencies	103	39	12	0	8	13	0	12
Percentage of Inconsistencies	51.2	59.1	57.1	0.0	57.1	39.4	0.0	75.0

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GRAVITY MEASUREMENTS IN SOUTHERN ONTARIO

BY

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Gravity Measurements in Southern Ontario

By L. G. D. Thompson and A. H. Miller

ABSTRACT

The results of over 1,000 gravity observations made in southern Ontario up to 1952 have been adjusted to a common datum and are presented in the form of tables of principal facts and two Bouguer anomaly maps. A general analysis of the anomaly pattern is given which leads to the conclusion that the overlying Palaeozoic rocks have little effect on the regional gravity pattern and it is believed that the major anomaly trends are caused by belts of different densities in the Precambrian basement.

INTRODUCTION

In the area usually designated as southern Ontario, which extends from the Ottawa and Mattawa Rivers southwards to Windsor, more than 1,000 gravity meter observations were made by the Dominion Observatory from 1945 to 1952. Fewer than 400 are distributed over the entire area and most of these constitute the earliest gravity meter work done in the area in 1945 and 1946. The remaining stations (over 600) are concentrated in the area east of Ottawa and were established in 1951 and 1952.

The early work was done with Humble and Atlas instruments and large discrepancies in the results from instrument calibration and erratic drift rates made it difficult to correlate the data year by year. In 1952, however, a network of primary gravity bases was established (Innes and Thompson, 1953) which provided a basis for adjusting this work to a common datum. Recomputation of all the original field results thus gave gravity values sufficiently accurate for use in preparing a Bouguer anomaly map of southern Ontario. This map, on a scale of 20 miles to the inch, was prepared chiefly to present the data available and to provide a regional gravity map of the area consistent with the set being systematically prepared for all of Canada. While it is recognized that the early surveys left large gaps in the regional coverage (usually in areas of difficult access) further work has not been done to complete the data but rather a special effort was made to concentrate the more recent work in the Ottawa-St. Lawrence lowland. This area was surveyed in great detail in 1951 and 1952 with better type gravity meters to permit a study of a complete regional gravity picture over an area where the geology is well known (Wilson, 1946). The anomaly map of this area on a scale of 4 miles to the inch is adequate for interpretation of the regional gravity anomalies.

While the Ottawa-St. Lawrence lowland is the only area surveyed in detail by the Dominion Observatory, several of the more interesting areas in the rest of southern Ontario have been studied in detail by other sources. The gravity anomalies in southwestern Ontario have been discussed by Brant (1943), with reference to the gas and oil fields. The great low at Mattawa has been dealt with by Garland (1950, 1953). University graduate students have carried out detailed gravity surveys in certain areas as projects for theses; these include the area around Georgian Bay (Uffen, 1950), the Sarnia-Windsor area (Prendergast, 1951), the Huntsville-Parry Sound area of anomalous high gravity (Oldham, 1952), and the Clare River syncline area near Actinolite (Fitzpatrick, 1950). Now that a primary base network has been established, each of these individual works can be reduced to the same datum and as it is expected that the universities will continue investigating local anomalies in this area, eventually more complete information will be available for the whole of southern Ontario.

This report is therefore a compilation of all gravity data available in southern Ontario up to the end of 1952. A general analysis of the cause of the regional anomaly trends is given, based on the information from a detailed survey of the Ottawa-St. Lawrence lowland. Two Bouguer anomaly maps are presented as well as tables of principal facts for all stations. Descriptions of the sites of primary bases in southern Ontario are included for further reference.

THE GRAVITY OBSERVATIONS

History of Field Work

The first gravity meter work by the Dominion Observatory in southern Ontario was carried out in 1945 using a Humble* gravity meter. Since that time the Observatory has obtained several gravity meters of the Atlas (Mott-Smith), North American, and Worden types which have also been used in this area. The extent to which each instrument has been employed is indicated by the station markings on the anomaly maps and in the following summary of field work (Table I).

TABLE I

Summary of Field Work

Year	No. of Stations	Instrument	Observer
1945	169	Humble	A. H. Miller
1946	112	Atlas	A. H. Miller
1947	4	Atlas	A. H. Miller
1948	71	Atlas	A. H. Miller
1949	25	Atlas	A. H. Miller
1951	93	Atlas	M. Sullivan
1951	332	North American 85	R. Bedford
1951	3	Worden 44 (by air)	L. G. D. Thompson
1952	123	Worden 44	J. A. Robinson
1952	108	North American 85 Worden 44 (base network)	L. G. D. Thompson R. Bedford J. A. Robinson

Gravity work carried out in 1950 by Saxov in the vicinity of Ottawa has been presented in a separate report (Saxov, 1956) and has not been included here.

* This instrument belonged to the Humble Oil and Refining Company of Houston, Texas, and was placed at the disposal of the Dominion Observatory through the courtesy of the American Geophysical Union.

Adjustment of Observations

The 1952 base network (Innes and Thompson, 1953) has provided control for the adjustment of all observations in the area. The scale constants as determined in 1952 for both the North American 85 and Worden 44 instruments have been used in computing the observed gravity for stations established with those meters. The Atlas gravimeter has not been directly calibrated against the primary bases. However, many of the stations observed with this instrument have been re-occupied with the North American and Worden meters and it has been found that in most cases the Atlas values are in close agreement with those determined with the other instruments. It has been concluded that the Atlas scale constant, as supplied by the manufacturer, is not seriously in error and has been used for computation purposes. No adequate check on the scale constant for the Humble instrument was possible. By adjusting the Humble stations directly to the primary bases, much of the error due to erratic drift of the instrument has been eliminated, although any error due to calibration remains.

Principal Facts

The principal facts for all stations presented in this report are given in Appendix A. They are grouped in chronological order according to the year in which the work was done and also the instrument used. The stations are tabulated primarily in their original sequence of observation but some have been compiled according to increasing latitude.

The observed gravity values have been computed to the tenth milligal. Since the stations observed with the North American, Worden, and Atlas instruments have been adjusted directly to the primary base network, they are considered to have a random error of the order of ± 0.1 milligal. The Humble results are much less reliable but have been included to provide all possible data for contouring purposes.

Observations were taken wherever possible at bench marks, railway stations, and railway crossings where precise elevations were known, and the gravity station elevation was taken to the nearest foot. Some elevations were determined by altimeter and although several of these have been checked and found to be within 1 or 2 feet of the true elevation, it is possible that some may be in error by 5 feet or more. An error of one foot in elevation introduces an error of 0.1 milligal in the Free Air and Bouguer anomalies.

The latitude and longitude for all stations have been scaled to a tenth of a minute from 1- and 2-mile maps where available, and 8-mile maps otherwise. Measurements from 1- and 2-mile maps may be in error by a tenth of a minute while those from 8-mile maps may be in error as much as five tenths. An error of one tenth of a minute in latitude introduces an error of about 0.15 milligal in the theoretical gravity, and hence in the anomaly values.

The Free Air and Bouguer anomalies have been computed to the tenth milligal on the basis of the International Formula as tabulated by Swick (1942), with a mean rock density of 2.67 grams per cubic centimeter. The accuracy of the anomaly values is difficult to assess because of the cumulative uncertainties in the observed gravity, elevation, and station position. With the exception of the Humble stations it is believed that the Bouguer anomalies are accurate to within one milligal which is adequate for defining regional anomalies. In the case of re-occupied stations other than bases, and those too close to be plotted separately, the most recent anomaly values have been used.

Descriptions of Sites of Primary Gravity Bases

Descriptions of all primary bases established in 1952 in southern Ontario, including those from North Bay to Sault Ste. Marie, are presented in Appendix B. Each diagram is oriented with the approximate north direction towards the top of the drawing. While the distances shown in the diagram are exact, it should be mentioned that neither the scale nor the configuration of structures or terrain are necessarily exact.

ANOMALOUS GRAVITY IN SOUTHERN ONTARIO

The Gravity Anomaly Map of Southern Ontario

This map covers the entire area on a scale of 20 miles to the inch with stations at an average interval of about 12 miles and a gravity contour interval of 5 milligals. Some stations around Montreal and from North Bay to Sault Ste. Marie have been included to complete the information in the area. Since the station interval is relatively large and there are large areas with no observations, and since most of the station values are from the earliest surveys and have the largest errors, it is evident that only the most regional anomalies are significant and in general are not adequate for detailed interpretation.

The most prominent feature shown by the anomaly contours on this map is the presence of alternate bands of high and low anomalous gravity having a roughly northeast-southwest trend. In the northeast corner of the map, which is discussed in the next section, the contours are crowded and the bands well defined and quite narrow, being about 20 miles across. To the west the bands become much broader and more irregularly defined.

Two very broad and intense gravity lows predominate in southern Ontario. One is well defined to the northwest of Toronto extending from Guelph to Newmarket. The other low surrounds Mattawa on the Ottawa River and while it is not completely defined, it contains the most negative anomaly value in the area of −68 milligals.

Several gravity highs are also defined in the area. One very regional anomaly extends around Lake St. Clair to Windsor. Another more local high appears just west of Huntsville. Two other highs with a more or less regional trend occur at Madoc and Renfrew. North of Cornwall is an area of extremely high gravity which trends southeast across the St. Lawrence River. In this region at a point 14 miles southwest of Hawkesbury the most positive anomaly of +7 milligals is found.

While it is not intended to give a detailed analysis here of the regional anomalies in southern Ontario, some general comments may be presented. The Palaeozoic cover* over most of the area appears to have little effect on the regional gravity contours. The Palaeozoics are very thin at the southern edge of the Precambrian Shield, which extends from Kingston to Midland, but dip gradually to the southwest until near Windsor they

* The Palaeozoic geology of much of southwestern Ontario is given in reports by Caley (1940, 1941, 1945).

have a depth of about 4,000 feet. The contacts for all Palaeozoic formations are encountered to the southwest and their strike is roughly northwest-southeast, yet the anomaly contours cross them at almost right angles without noticeable interruption. Even the contact of the Ordivician and Silurian, which is characterized by the presence of an escarpment and ridge between Hamilton and Owen Sound, is not indicated.

The densities of the Palaeozoic rocks in southwestern Ontario have been given by Brant (1943) as being between 2.68 and 2.82 grams per cubic centimeter which is the same range as may be expected for densities in the Precambrian basement. Brant has also shown that for southwestern Ontario, structures in the Palaeozoic column do not give rise to gravity anomalies greater than 0.3 milligal and has concluded that "density differences and structures must exist in the Precambrian which account for practically the whole magnitude of the gravity anomalies observed". With a contour interval of 5 milligals it is apparent that for the anomalies shown on this map, the same conclusion is applicable to the entire area.

The Gravity Anomaly Map of the Ottawa-St. Lawrence Lowland

This map covers the area south and east of Ottawa on a scale of 4 miles to the inch and coincides with the Ottawa-Cornwall sheet (Geol. Surv., Canada, map 852 A). This area has been surveyed in great detail with better type gravity meters and with stations only 1 to 2 miles apart. Since the stations are so close together and the results are of a high degree of accuracy, a 2.5-milligal contour interval has been used to outline the regional anomalies.

With a greater number of stations (a smaller station interval) per unit area the anomalies are clearly defined and many more local highs and lows appear. The regional anomaly pattern of alternate bands of high and low gravity having a northeast-southwest trend is emphasized in this area. A trough of low gravity extends from Brockville northeasterly to Pendleton and on into Quebec. This is flanked on the west side by a parallel ridge of relatively high gravity which crosses the Ottawa River at Buckingham, Quebec. On the east side of the low is a series of positive gravity anomalies extending from near Morrisburg to Pointe au Chêne, Quebec. In the vicinity of McCrimmon, 14 miles southwest of Hawkesbury, the positive anomaly is greatest and spreads out to the southeast to enclose that part of Quebec east of the St. Lawrence River, and continues southwards into the State of New York. The values of gravity become increasingly positive in the southeasterly direction. In Quebec, north of this region of high gravity, is an area of many small local gravity lows.

A general analysis of the anomalous gravity may be considered. Assuming that the effect of overlying Palaeozoics is negligible, the ridges and troughs of high and low gravity respectively may primarily be caused by three features in the Precambrian basement. Firstly, the basement topography may be irregular, forming long ridges which come much nearer to the surface than the intervening valleys; secondly, there may be belts of more dense or less dense phases in the granite or granite gneiss than normal and thirdly, there may be areas that have been intruded by basic flows which may extend in great bodies below the surface of the Precambrian to account for the high gravity anomalies. From the structure sections shown in the Ottawa-Cornwall sheet (map 852 A) prepared by Wilson (1946) and reproduced in Figure 1, it appears that the Precambrian surface is quite flat without any undulating ridges. Thus it seems that the second and third causes are more likely responsible for the anomalies in this area.

Gravity anomaly profiles over the two structure sections of Wilson are shown in Figure 1. One profile runs southeast from Ottawa to Cornwall across the regional anomaly trends, and the other runs south to north from near Prescott to Blackburn (just east of Ottawa) angling slightly across a belt of extremely low gravity. The former profile shows a sinusoidal variation in gravity irrespective of the presence of varying thicknesses of Palaeozoic formation, which supports the assumption made earlier. The latter shows a distinct trough of more negative gravity occurring over a very regular geological terrain where the overlying Palaeozoics are flat-lying, of nearly uniform thickness, and of shallow depth. This trough occurs over a region where small knolls in the Precambrian rise close to the surface and in some cases are exposed. These knobs are Precambrian quartzite and while they are not individually identified by the gravity contours because the station interval and contour interval are too large, their distribution (by outcrops) indicates that the quartzite may exist in a belt about 5 miles wide trending northeasterly from Brockville, which coincides with the trough of low gravity. Numerous samples of this quartzite taken from available outcrops gave a mean density of 2.62 gms. per cc. which is less than that usually found for dense granite gneisses, pyroxene syenites, and Grenville crystalline limestone also found in the Precambrian basement. Without density samples of the surrounding Precambrian rocks it is impossible to continue the investigation further. However, it is apparent that the gravity low occurs over an area where relatively light quartzites are found and it is reasonable to infer that there appears to be an association between the trough of low gravity and a lighter quartzitic phase in the Precambrian basement.

An indication of the cause of the high gravity anomalies is obtained from a study of the geology of the exposed Precambrian Shield north of the Ottawa River (*see* Geol. Surv., Canada, map 703 A, Southern Quebec, West sheet). At Buckingham, Quebec, where a ridge of high gravity crosses the Ottawa River, the predominant regional rocks are of the Grenville series; crystalline limestone, quartzite, quartz-biotite schist, gneiss; minor granite, granite gneiss and basic intrusives. Just in the vicinity of Buckingham are numerous basic rocks of the Buckingham series described (Wilson, 1920) as "pyroxene syenite, diorite, monzonite; gabbro, anorthosite, peridotite pyroxenite". These rocks have densities slightly greater than those of the Grenville series (Thompson and Garland, 1957) and are likely responsible for the local gravity high in this area. Since these basic rocks are believed to continue in the basement south of the Ottawa River, it seems reasonable to assume an association between them and the ridge of high gravity.

The intense positive gravity anomaly appearing at the southeast corner of the area is now known to extend across the St. Lawrence River to Huntingdon, Quebec, where it reaches a value of + 20 milligals, (Thompson and Garland, 1957). The anomaly continues into New York State and is believed to be associated with a belt of gabbro in the district of Malone, N.Y. The gravity high north of the St. Lawrence River is the expression of the northwesterly limit of this anomaly.

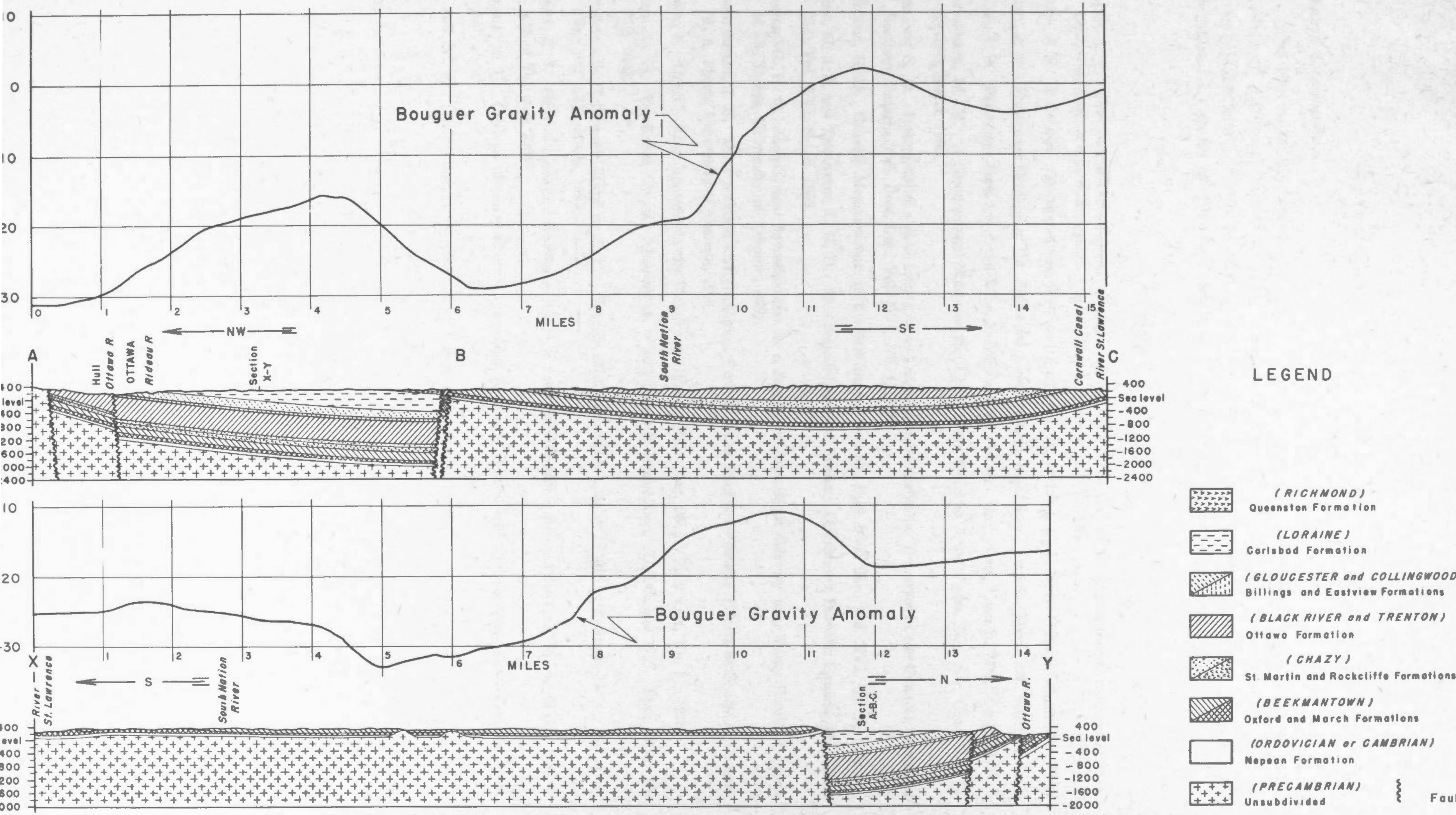

Figure 1. Gravity Profiles over Structure Sections by A. E. Wilson in the Ottawa-St. Lawrence Lowland.

General Conclusions

The two anomaly maps show that the major anomaly pattern in southern Ontario consists of alternate bands of high and low gravity trending in a southwesterly-northeasterly direction. From available evidence it is considered that these anomaly trends are caused by belts of different densities in the Precambrian basement.

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General Conclusions

The [illegible] anomaly maps show that [illegible] consists of alternate bands of high and low [illegible] gravity anomalies. These [illegible] are caused by belts of different densities in the Precambrian [illegible].

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APPENDIX A

Principal Facts

C = 0.176 mgals/div. PRINCIPAL FACTS FOR GRAVITY STATIONS, 1945 **Humble**

Station No.	Station Name	Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
1	Graham Bay	75° 48'.3	45° 20'.7	222 ft.	980.6202	−0.0194	−0.0270
2	South March	75 54.8	45 20.2	283	.6144	− .0189	− .0285
3	Carp	76 02.2	45 20.6	311	.6099	− .0210	− .0318
4	Kinburn	76 11.3	45 23.3	310	.6091	− .0261	− .0367
5	Glasgow	76 30.5	45 26.7	444	.6198	− .0079	− .0231
6	Douglas	76 56.2	45 30.5	416	.6218	− .0144	− .0285
7	Golden Lake	77 15.5	45 34.4	586	.6024	− .0236	− .0435
8	Killaloe	77 24.9	45 33.3	590	.5981	− .0260	− .0461
9	Wilno	77 33.9	45 30.6	955	.5691	− .0155	− .0490
10	Combermere	77 37.0	45 22.8	940	.5629	− .0124	− .0444
11	Maynooth	77 54.8	45 13.9	1302	980.5309	+0.0031	−0.0413
12	Turriff	77 44.6	44 58.9	1096	.5278	+ .0032	− .0341
13	Brinklow	77 41.9	44 53.6	1145	.5218	+ .0097	− .0293
14	Gilmour	77 36.8	44 49.2	1013	.5230	+ .0052	− .0293
15	Bannockburn	77 33.0	44 38.8	831	.5270	+ .0077	− .0206
16	Ivanhoe	77 28.2	44 25.0	611	.5125	− .0067	− .0275
17	Holloway	77 27.9	44 17.1	427	.5095	− .0152	− .0298
18	Marysville	77 06.6	44 13.6	337	.5097	− .0182	− .0297
19	Odena	76 43.3	44 16.6	397	.5077	− .0191	− .0326
20	Jct. to Rideau	76 18.3	44 18.4	282	.5215	− .0188	− .0284
21	Gananoque	76 09.7	44 19.4	255	980.5270	−0.0173	−0.0260
22	Lansdowne	76 01.0	44 24.2	337	.5262	− .0176	− .0291
23	Mallorytown	75 53.2	44 28.7	334	.5344	− .0165	− .0279
24	Brockville Stn.	75 41.6	44 35.6	283	.5462	− .0199	− .0295
25	Cardinal	75 23.3	44 47.8	279	.5831	− .0017	− .0112
26	Williamsburg	75 16.3	45 00.9	248	.6035	− .0049	− .0133
27	Greely	75 33.8	45 15.7	307	.6230	− .0011	− .1167
28		75 36.9	45 20.4	313	.6240	− .0066	− .0172
29	Meath	76 59.6	45 44.0	417	.6318	− .0246	− .0388
30	Petawawa	77 17.0	45 53.8	466	.6354	− .0312	− .0470
31	Chalk River	77 27.2	46 01.0	521	980.6399	−0.0322	−0.0499
32	Port Alexander	77 33.6	46 08.3	535	.6506	− .0312	− .0494
33	Mackey	77 49.5	46 12.0	432	.6598	− .0373	− .0520
34	Bissett	78 04.8	46 13.8	559	.6553	− .0325	− .0516
35	Deux Rivières	78 17.3	46 14.9	520	.6449	− .0482	− .0659
36	Klock	78 29.5	46 17.3	528	.6443	− .0516	− .0696
37	Mattawa (Hosp.)	78 42.4	46 19.0	541	.6489	− .0490	− .0674
38	Poliva Creek (bridge.)	78 51.8	46 16.9	586	.6453	− .0446	− .0645
39	Corbeil	79 17.8	46 15.9	735	.6424	− .0320	− .0570
40	Powassan	79 21.5	46 04.8	854	.6171	− .0295	− .0586
41	South River	79 22.5	45 50.4	1158	980.5890	−0.0073	−0.0467
42	Burks Falls	79 23.7	45 37.4	970	.5945	+ .0001	− .0329
43	Emsdale	79 19.0	45 31.8	1039	.5900	+ .0105	− .0249
44	Novar	79 15.0	45 26.0	1072	.5747	+ .0070	− .0295
45	Dwight	79 00.8	45 19.7	1043	.5646	+ .0037	− .0318
46	Algonquin Pk. West Entrance	78 51.2	45 25.2	1359	.5505	+ .0110	− .0353
47	Smoke Creek	78 42.9	45 30.9	1377	.5557	+ .0093	− .0376
48	Opeongo L. Jct.	78 19.5	45 35.5	1385	.5546	+ .0021	− .0451
49	Madawaska	77 59.4	45 30.1	1034	.5645	− .0129	− .0482
50	Stream to Bark L.	77 50.9	45 30.1	1023	.5638	− .0147	− .0495

C=0.176 mgals/div. PRINCIPAL FACTS FOR GRAVITY STATIONS, 1945 **Humble**

Station		Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies	
No.	Name					Free Air	Bouguer
51	L'Amable Creek	78° 06.'4	45° 28.'8	1195 ft.	980.5548	−0.0055	−0.0462
52	Stream to Whitefish L.	78 26.4	45 34.3	1300	.5577	− .0010	− .0453
53	Bracebridge	79 18.6	45 02.3	812	.5506	− .0061	− .0338
54	Falkenburg	79 21.0	45 05.9	952	.5500	+ .0012	− .0312
55	Severn	79 20.2	44 46.3	727	.5302	− .0102	− .0350
56	Brechin	79 10.8	44 32.7	755	.5000	− .0173	− .0430
57	Beaverton	79 09.1	44 26.0	750	.4886	− .0191	− .0446
58	Greenbank	78 00.9	44 09.1	992	.4558	− .0037	− .0375
59	Myrtle	78 58.1	44 01.1	888	.4461	− .0111	− .0413
60	Rosebank	79 06.8	43 47.8	290	.4645	− .0290	− .0389
61	Danforth	79 18.0	43 41.2	426	980.4441	−0.0267	−0.0412
62	422 Mortimer	79 20.1	43 41.3	410	.4458	− .0266	− .0406
63	Islington	79 32.0	43 39.2	403	.4429	− .0270	− .0407
64	Clarkson	79 37.6	43 31.1	321	.4358	− .0291	− .0400
65	Bronte	79 44.1	43 24.4	344	.4232	− .0270	− .0388
66	Aldershot	79 51.6	43 18.6	341	.4118	− .0330	− .0446
67	Capetown	80 03.7	43 14.7	748	.3766	− .0241	− .0496
68	Harrisburg	80 12.5	43 14.0	737	.3786	− .0221	− .0472
69	Gobles	80 34.2	43 09.7	940	.3617	− .0135	− .0455
70	Ingersoll	80 53.1	43 02.4	880	.3560	− .0138	− .0438
71	Thamesford	81 00.1	43 03.7	950	980.3564	−0.0088	−0.0412
72	London (C.P.R.)	81 15.1	42 59.6	804	.3601	− .0127	− .0401
73	Mount Brydges	81 29.6	42 54.3	819	.3537	− .0098	− .0377
74	Melbourne	81 33.1	42 49.2	733	.3532	− .0107	− .0356
75	Appin	81 38.8	42 47.7	741	.3516	+ .0008	− .0244
76	Newbury	81 47.8	40 40.1	702	.3455	− .0077	− .0316
77	Alvinston	81 52.0	40 49.1	731	.3597	− .0042	− .0291
78	Petrolia	82 08.9	40 53.0	667	.3733	+ .0015	− .0212
79	Forest	82 00.2	43 05.7	712	.3905	− .0001	− .0244
80	Thedford	81 51.3	43 09.8	682	.3951	− .0045	− .0277
81	Parkhill	81 41.4	43 09.8	662	980.3923	−0.0091	−0.0317
82	Ilderton	81 23.0	43 04.8	933	.3665	− .0019	− .0337
83	Clandeboye	81 27.4	43 11.9	883	.3823	− .0015	− .0316
84	Exeter	81 29.4	43 21.1	871	.3936	− .0052	− .0348
85	Kippen	81 30.8	43 28.1	885	.4029	− .0051	− .0352
86	Clinton	81 32.3	43 36.7	925	.4150	− .0021	− .0336
87	Blyth	81 25.6	43 44.3	1050	.4172	− .0005	− .0363
88	Wingham	81 18.3	43 53.3	1046	.4302	− .0004	− .0360
89	Teeswater	81 17.1	43 59.6	1020	.4387	− .0039	− .0386
90	Walkerton	81 09.7	44 07.0	932	.4527	− .0092	− .0410
91	Chesley	81 06.8	44 17.5	921	980.4684	−0.0105	−0.0418
92	Dobbinton	81 08.6	44 23.6	816	.4817	− .0161	− .0439
93	Tara	81 08.9	44 28.5	756	.4929	− .0180	− .0437
94		80 45.5	44 35.5	1165	.4864	+ .0033	− .0364
95	Meaford	80 35.5	44 36.4	603	.5234	− .0138	− .0343
96	Thornbury	80 26.7	44 33.6	612	.5177	− .0144	− .0353
97	Collingwood	80 12.8	44 30.2	589	.5103	− .0189	− .0390
98	Stayner	80 05.2	44 25.2	713	.4906	− .0193	− .0436
99		79 56.6	44 26.1	658	.4953	− .0213	− .0437
100	Minesing	79 46.0	44 26.4	622	.4996	− .0207	− .0419

C=0.176 mgals/div. PRINCIPAL FACTS FOR GRAVITY STATIONS, 1945 Humble

Station No.	Station Name	Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
101	Barrie	79° 41'.3	44° 23'.3	727 ft.	980.4855	−0.0203	−0.0451
102	Lefroy	79 33.4	44 15.6	769	.4679	− .0224	− .0486
103	Bradford	79 33.4	44 07.0	723	.4525	− .0292	− .0538
104	Aurora	79 27.6	44 00.1	831	.4321	− .0290	− .0573
105	Richmond Hill	79 25.8	43 52.8	746	.4340	− .0241	− .0495
106	Woodbridge	79 36.0	43 47.3	554	.4383	− .0297	− .0486
107	Inglewood	79 56.1	43 47.8	897	.4117	− .0247	− .0553
108	Shelburne	80 12.3	44 04.6	1629	.4028	+ .0099	− .0456
109	Dundalk	80 23.6	44 10.2	1705	.4059	+ .0119	− .0462
110	Flesherton	80 34.4	44 14.9	1558	.4228	+ .0077	− .0453
111	Markdale	80 39.1	44 18.8	1361	980.4454	+0.0060	−0.0403
112	Holland Centre	80 47.7	44 23.5	1216	.4643	+ .0042	− .0372
113	Chatsworth	80 53.4	44 27.1	945	.4860	− .0060	− .0382
114	Hepworth	81 08.7	44 39.8	716	.5107	− .0210	− .0453
115	Wiarton	81 08.3	44 44.5	596	.5301	− .0199	− .0402
116	Durham	80 49.3	44 10.5	1127	.4503	+ .0011	− .0373
117	Holstein	80 45.6	44 03.7	1335	.4205	+ .0014	− .0441
118	Kenilworth	80 38.2	43 54.2	1486	.3956	+ .0035	− .0471
119	Arthur	80 32.0	43 50.5	1527	.3848	+ .0035	− .0485
120	Fergus	80 23.2	43 42.0	1359	.3788	− .0055	− .0518
121	Acton	80 02.1	43 38.0	1158	980.3824	−0.0148	−0.0542
122	Rockwood	80 08.8	43 37.2	1182	.3785	− .0152	− .0555
123	Elmira	80 33.0	43 36.0	1146	.3859	− .0094	− .0484
124	Waterloo	80 31.3	43 27.9	1058	.3792	− .0121	− .0481
125	Galt	80 19.0	43 22.1	936	.3748	− .0193	− .0511
126	New Hamburg	80 42.8	43 23.0	1128	.3685	− .0090	− .0474
127	Stratford	80 58.5	43 21.8	1192	.3678	− .0019	− .0425
128	St. Mary's	81 08.2	43 15.5	1056	.3719	− .0011	− .0370
129	Shakespeare	80 50.8	43 21.9	1178	.3678	− .0033	− .0434
130	Hickson	80 48.3	43 14.3	1094	.3595	− .0081	− .0454
131	Burgessville	80 39.2	43 01.5	908	980.3524	−0.0135	−0.0444
132	Otterville	80 35.7	42 55.7	796	.3519	− .0158	− .0429
133	Delhi	80 30.1	42 50.9	764	.3422	− .0213	− .0474
134	Waterford	80 17.8	42 55.9	760	.3518	− .0196	− .0455
135	Mt. Pleasant	80 19.9	43 04.7	790	.3636	− .0181	− .0450
136	Onondago	80 07.1	43 07.2	666	.3743	− .0229	− .0455
137	Hagersville	80 03.3	42 57.8	730	.3581	− .0189	− .0438
138	Caledonia	79 57.1	43 04.7	659	.3743	− .0197	− .0422
139	Rymal	79 50.9	43 11.5	641	.3877	− .0183	− .0401
140	Oshawa	78 51.7	43 53.5	346	.4723	− .0246	− .0363
141	Bowmanville	78 41.4	43 54.9	365	980.4715	−0.0257	−0.0381
142	Newtonville	78 29.5	43 56.9	539	.4569	− .0261	− .0445
143	Cobourg	78 09.9	43 57.6	261	.4737	− .0373	− .0461
144	Grafton	78 01.1	43 58.7	284	.4782	− .0322	− .0419
145	Brighton	77 44.0	44 02.6	324	.4913	− .0213	− .0324
146	Tweed	77 19.1	44 23.7	484	.5204	− .0089	− .0254
147	Actinolite Jct. 7, 37	77 19.3	44 33.0	560	.5323	− .0038	− .0229
148	Kaladar	77 07.0	44 38.7	701	.5224	− .0090	− .0328
149	Ardendale	76 56.8	44 43.1	620	.5327	− .0130	− .0341
150	Sharbot Lake	76 41.4	44 46.4	648	.5435	− .0045	− .0266

C=0.176 mgals/div. PRINCIPAL FACTS FOR GRAVITY STATIONS, 1945 **Humble**

Station No.	Station Name	Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
151	Bathurst	76° 23!2	44° 52!1	483 ft.	980.5610	−0.0111	−0.0275
152	Ashton	76 03.3	45 10.4	448	.5875	− .0155	− .0307
153	Franktown	76 04.7	45 01.6	482	.5752	− .0113	− .0277
154	Stittsville	75 55.2	45 15.5	399	.5981	− .0171	− .0307
155	Templeton	75 36.4	45 29.7	160	.6466	− .0125	− .0179
156	Buckingham Jct.	75 25.2	45 32.8	190	.6567	− .0041	− .0106
157	Thurso	75 14.7	45 35.9	186	.6515	− .0144	− .0207
158	Plaisance	75 06.8	45 36.5	184	.6397	− .0273	− .0336
159	Montebello	74 56.5	45 39.3	171	.6525	− .0199	− .0257
160	Pte. au Chêne	74 44.8	45 38.6	187	.6707	− .0009	− .0055
161	Pte. Fortune	74 23.2	45 33.8	120	980.6464	−0.0225	−0.0266
162	Rigaud	74 18.0	45 28.9	104	.6390	− .0241	− .0277
163	St. Esprit	73 39.9	45 54.2	205	.6737	− .0179	− .0249
164	St. Canut	74 04.9	45 43.1	247	.6557	− .0154	− .0238
165	Staynerville	74 25.5	45 38.3	259	.6367	− .0259	− .0348
166	Vankleek Hill	74 38.8	45 32.1	270	.6461	− .0062	− .0154
167	Monckland	74 52.8	45 11.8	333	.6243	+ .0085	− .0028
168	Finch	75 05.2	45 08.8	275	.6203	+ .0036	− .0058
169	Chesterville	75 13.9	45 06.4	240	.6110	− .0054	− .0136

C=0.27714 mgals/div. PRINCIPAL FACTS FOR GRAVITY STATIONS, 1946 **Atlas**

Station No.	Station Name	Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
1	Stonecliff	77° 53!6	46° 12!9	475 ft.	980.6602	−0.0342	−0.0504
2	Chapeau	77 04.6	45 55.0	359	.6476	− .0307	− .0430
3	Waltham	76 54.5	45 54.6	368	.6558	− .0211	− .0336
4	Davidson	76 45.9	45 52.2	365	.6573	− .0163	− .0287
5	Fort Coulonge	76 44.3	45 50.4	367	.6560	− .0147	− .0272
6	Vinton	76 36.9	45 47.0	368	.6521	− .0134	− .0259
7	Campbell Bay	76 36.2	45 44.0	363	.6522	− .0093	− .0216
8	Shawville	76 29.5	45 36.3	571	.6290	− .0013	− .0207
9	Wyman	76 18.1	45 31.8	398	.6357	− .0141	− .0276
10	Quyon	76 14.4	45 31.3	279	.6276	− .0227	− .0322
11	Breckenridge	75 57.3	45 28.9	219	980.6281	−0.0242	−0.0317
12	Wilsonvale	74 11.0	45 18.1	162	.6459	+ .0045	− .0010
13	Farran's Point	75 00.2	44 59.1	242	.6181	+ .0129	+ .0046
14	Brockville Stn.	75 41.6	44 35.6	283	.5469	− .0192	− .0288
15	Forthton	75 51.7	44 38.4	409	.5462	− .0122	− .0262
16	Toledo	75 59.3	44 44.0	401	.5607	− .0069	− .0205
17	Smith's Falls	76 01.0	44 54.2	427	.5764	− .0041	− .0187
18	Lombardy	76 05.1	44 48.7	433	.5559	− .0158	− .0305
19	Portland	76 11.3	44 42.0	480	.5421	− .0151	− .0314
20	Crosby	76 15.5	44 39.2	414	.5421	− .0172	− .0313
21	Elgin	76 14.7	44 37.5	414	980.5406	−0.0160	−0.0301
22	Morton	76 12.0	44 32.4	329	.5385	− .0185	− .0297
23	Seeley's Bay	76 14.2	44 28.5	359	.5309	− .0173	− .0296
24	Joyceville	76 19.6	44 22.9	344	.5264	− .0148	− .0266

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Station		Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies	
No.	Name					Free Air	Bouguer
25	Rideau	76° 25′.7	44° 17′.8	320 ft.	980.5173	− .0185	− .0294
26	Cataraqui	76 35.5	44 15.9	364	.5098	− .0190	− .0314
27	Collin's Bay	76 36.9	44 14.5	286	.5104	− .0236	− .0333
28	Bath	76 46.6	44 11.2	250	.5053	− .0272	− .0357
29	Adolphustown	77 00.0	44 04.2	294	.4959	− .0219	− .0320
30	Picton	77 09.0	44 00.5	313	.4906	− .0199	− .0305
31	Bloomfield	77 14.0	43 59.2	258	980.5005	−0.0131	−0.0219
32	Mountain View	77 22.4	44 04.8	291	.5018	− .0172	− .0271
33	Madoc Cabin	77 28.9	44 30.5	575	.5224	− .0085	− .0281
34	Marmora	77 39.0	44 30.3	595	.5158	− .0129	− .0332
35	Norwood	77 59.1	44 23.3	672	.4910	− .0200	− .0429
36	Indian River	78 08.4	44 20.6	712	.4866	− .0165	− .0408
37	Omemee	78 33.7	44 18.1	829	.4746	− .0138	− .0421
38	Reaboro	78 38.6	44 19.1	849	.4764	− .0116	− .0406
39	Oakwood	78 52.7	44 20.0	908	.4738	− .0100	− .0409
40	Blackwater	79 02.9	44 14.2	861	.4689	− .0106	− .0399
41	Kleinburg	79 37.9	43 50.6	713	980.4308	−0.0271	−0.0514
42	Bolton	79 44.5	43 52.2	848	.4238	− .0238	− .0527
43	Palgrave	79 50.1	43 57.0	932	.4197	− .0272	− .0590
44	Orangeville (lodge)	80 06.0	43 55.7	1450	.3904	− .0059	− .0553
45	Waldemar	80 16.6	43 53.6	1494	.3864	− .0026	− .0535
46	Palmerston	80 51.0	43 50.0	1315	.4052	+ .0048	− .0400
47	Listowel	80 58.0	43 44.2	1262	.4019	+ .0114	− .0316
48	Atwood	81 01.3	43 40.0	1200	.4001	+ .0039	− .0370
49	West Monkton	81 04.9	43 35.4	1194	.3941	+ .0042	− .0365
50	Mitchell	81 11.9	43 27.8	1119	.3799	− .0056	− .0438
51	Kirkton	81 18.8	43 19.4	1004	980.3873	+0.0036	−0.0309
52	Lobo	81 25.4	43 00.0	905	.3578	− .0061	− .0369
53	Strathroy	81 37.6	42 57.5	741	.3656	− .0100	− .0352
54	Kerwood	81 44.5	42 56.8	769	.3651	− .0068	− .0330
55	Watford	81° 52′.9	42° 56′.8	786	.3687	− .0016	− .0283
56	Wyoming	82 07.3	42 56.9	708	.3777	− .0001	− .0242
57	Corunna	82 27.2	42 53.3	613	.3729	− .0084	− .0293
58	Bickford	82 27.4	42 45.9	598	.3591	− .0126	− .0329
59	Port Lambton	82 30.0	42 39.4	581	.3540	− .0095	− .0292
60	Wallaceburg Stn.	82 22.5	42 35.2	580	.3527	− .0045	− .0243
61	Dresden	82 10.0	42 35.2	601	980.3497	−0.0056	−0.0260
62	Eddy's	82 07.0	42 44.0	661	.3601	− .0027	− .0252
63	Oil Springs	82 07.3	42 47.0	659	.3651	− .0024	− .0249
64	Bothwell	81 53.8	42 38.7	661	.3491	− .0058	− .0283
65	Thamesville	81 58.3	42 36.9	620	.3410	− .0151	− .0362
66	Kent Bridge	82 04.0	42 31.0	607	.3410	− .0074	− .0281
67	St. Joachim	82 37.9	42 17.0	582	.3242	− .0057	− .0255
68	Elmstead	82 50.7	42 17.3	589	.3283	− .0013	− .0214
69	La Salle	83 06.1	42 13.9	579	.3243	− .0011	− .0209
70	Amherstburg	83 06.7	42 06.2	580	.3048	− .0090	− .0288
71	Harrow	82 55.0	42 02.4	623	980.2901	−0.0140	−0.0352
72	Kingsville	82 44.2	42 01.9	608	.2897	− .0151	− .0358
73	Leamington	82 35.9	42 03.4	620	.2906	− .0153	− .0364
74	Wheatley	82 27.7	42 06.5	606	.2992	− .0126	− .0332
75	Merlin	82 13.8	42 14.3	630	.3163	− .0049	− .0264

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Station No.	Station Name	Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
76	Charing Cross	82° 06'.3	42° 20'.2	628 ft.	980.3260	− .0043	− .0257
77	Blenheim	82 00.2	42 20.3	671	.3240	− .0024	− .0252
78	Morpeth	81 50.7	42 23.4	660	.3250	− .0070	− .0295
79	Jct. Hys. 3 and 77	81 37.7	42 31.4	658	.3300	− .0142	− .0366
80	Wallacetown	81 28.0	42 38.2	708	.3337	− .0160	− .0401
81	Shedden	81 20.9	42 44.6	720	980.3414	−0.0168	−0.0413
82	Paynes	81 16.3	42 47.5	752	.3435	− .0161	− .0417
83	Belmont	81 05.3	42 52.5	846	.3421	− .0161	− .0449
84	New Sarum	81 05.1	42 46.8	763	.3379	− .0195	− .0455
85	Aylmer	80 59.1	42 46.7	763	.3357	− .0216	− .0476
86	Tillsonburg	80 43.3	42 50.8	760	.3459	− .0178	− .0437
87	Mount Elgin	80 48.3	42 57.3	908	.3463	− .0133	− .0442
88	Simcoe (CNR-North)	80 18.6	42 51.1	723	.3464	− .0213	− .0459
89	Port Dover	80 11.9	42 47.2	576	.3528	− .0228	− .0424
90	Jarvis	80 06.6	42 53.5	699	.3533	− .0203	− .0441
91	Nelles Corners	79 57.3	42 55.7	717	980.3584	−0.0168	−0.0412
92	Canfield	79 45.0	42 58.5	622	.3722	− .0161	− .0373
93	Dunnville	79 36.8	42 54.3	587	.3664	− .0189	− .0389
94	Marchville	79 22.7	42 57.3	580	.3775	− .0129	− .0327
95	4-mi. West Port Colborne	79 10.9	42 53.5	588	.3690	− .0150	− .0350
96	Stevensville	79 03.4	42 56.4	584	.3743	− .0144	− .0343
97	Chippawa	79 03.5	43 03.6	573	.3873	− .0132	− .0327
98	Vineland	79 23.6	43 10.2	305	.4106	− .0254	− .0358
99	Grimsby Beach	79 31.5	43 11.5	302	.4103	− .0276	− .0379
100	Winona	79 38.8	43 12.9	284	.4127	− .0290	− .0387
101	Stoney Creek	79 45.1	43 14.4	272	980.4134	−0.0316	−0.0409
102	Puslinch	80 05.4	43 25.9	986	.3803	− .0149	− .0484
103	Guelph (Cabins)	80 14.9	43 32.4	1015	.3826	− .0196	− .0542
104	Erin	80 04.4	43 46.7	1293	.3845	− .0131	− .0571
105	Alton	80 03.8	43 51.5	1317	.3888	− .0137	− .0586
106	Concord	79 29.3	43 48.3	629	.4368	− .0256	− .0471
107	Unionville	79 18.7	43 51.8	575	.4474	− .0253	− .0449
108	Locust Hill	79 11.8	43 53.3	666	.4465	− .0200	− .0426
109	Bowmanville (Tourist)	78 40.3	43 54.7	300	.4767	− .0263	− .0365
110	Iroquois	75 18.2	44 50.9	245	.5941	+ .0014	− .0069
111	Williamsburg	75 14.7	44 58.6	275	980.6028	+0.0014	−0.0080
112	Orangeville Lodge	80 06.0	43 55.7	1450	.3906	− .0057	− .0551

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Station No.	Station Name	Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
1		76° 00'.0	45° 21'.1	384 ft.	980.6086	−0.0159	−0.0292
2	Renfrew Hotel	76 41.1	45 28.4	423	.6276	− .0047	− .0191
3	Petawawa	77 17.0	45 53.8	467	.6354	− .0310	− .0469
4	Mattawa Hospital	78 42.6	46 19.1	541	.6492	− .0483	− .0667

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Station No.	Station Name	Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
1	....	75° 42.1	45° 16.0	291 ft.	980.6193	−0.0068	−0.0167
2	....	75 41.3	45 20.6	317	.6226	− .0080	− .0188
3	Ramsayville..............	75 34.1	45 22.7	242	.6301	− .0106	− .0189
4	Carlsbad Springs.........	75 28.7	45 22.3	227	.6321	− .0094	− .0172
5	Vars......................	75 21.2	45 21.2	252	.6173	− .0203	− .0289
6	Russell...................	75 21.6	45 15.8	237	.6102	− .0207	− .0288
7	Embrun....................	75 17.2	45 16.3	225	.6111	− .0216	− .0293
8	Casselman.................	75 05.2	45 18.8	219	.6210	− .0161	− .0236
9	St. Isidore...............	74 54.3	45 23.1	213	.6464	+ .0023	− .0049
10	Eastview..................	75 38.9	45 26.5	230	.6315	− .0162	− .0240
11	Orleans...................	75 32.0	45 28.0	220	980.6447	−0.0061	−0.0136
12	....	75 20.9	45 31.3	177	.6512	− .0087	− .0147
13	....	75 13.1	45 34.7	178	.6463	− .0186	− .0246
14	....	75 07.4	45 34.0	174	.6401	− .0240	− .0300
15	Pendleton.................	75 03.7	45 27.9	231	.6252	− .0245	− .0323
16	Bourget...................	75 10.2	45 26.4	213	.6250	− .0241	− .0313
17	Hammond...................	75 14.3	45 26.2	218	.6274	− .0209	− .0283
18	Leonard...................	75 21.0	45 25.4	271	.6304	− .0117	− .0209
19	Navan.....................	75 26.3	45 25.0	239	.6358	− .0087	− .0169
20	Blackburn.................	75 33.1	45 26.2	281	.6347	− .0077	− .0172
21	Bridge Inn................	74 36.9	45 36.6	154	980.6561	−0.0139	−0.0192
22	L'Orignal.................	74 42.0	45 36.6	163	.6664	− .0028	− .0083
23	....	74 48.3	45 35.0	167	.6601	− .0063	− .0120
24	Alfred....................	74 53.6	45 31.9	177	.6461	− .0147	− .0207
25	McAlpine..................	74 42.0	45 32.0	220	.6556	− .0012	− .0087
26	Stardale..................	74 33.6	45 31.7	290	.6405	− .0093	− .0192
27	St. Eugene................	74 27.8	45 30.2	180	.6444	− .0135	− .0196
28	....	74 18.2	45 23.1	194	.6464	+ .0005	− .0061
29	Mille Roches..............	74 49.9	45 01.7	225	.6147	+ .0039	− .0038
30	Cornwall C.P.R............	74 44.0	45 01.5	184	.6183	+ .0039	− .0024
31	St. Andrews...............	74 48.5	45 05.3	236	980.6217	+0.0065	−0.0015
32	Harrison..................	74 54.2	45 05.1	291	.6195	+ .0098	+ .0001
33	....	74 55.8	45 07.5	352	.6204	+ .0128	+ .0008
34	Avonmore..................	74 58.1	45 10.6	327	.6243	+ .0098	.0014
35	Moose Creek...............	74 57.9	45 15.3	290	.6262	− .0011	− .0088
36	Maxville..................	74 51.4	45 17.1	336	.6351	+ .0116	+ .0002
37	Apple Hill................	74 46.2	45 13.0	301	.6261	+ .0054	− .0048
38	....	74 43.5	45 08.3	208	.6280	+ .0057	− .0014
39	Fairfield.................	74 34.0	45 03.3	178	.6252	+ .0075	+ .0015
40	River Baudette............	74 19.8	45 13.7	167	.6455	+ .0112	+ .0055
41	Bainsville................	74 24.9	45 11.1	174	980.6411	+0.0114	+0.0054
42	Lancaster.................	74 30.2	45 08.4	162	.6348	+ .0080	+ .0025
43	Glen Gordon...............	74 31.8	45 10.7	183	.6373	+ .0090	+ .0028
44	Green Valley..............	74 36.1	45 15.5	281	.6336	+ .0073	− .0022
45	Glen Robertson............	74 30.2	45 21.6	263	.6429	+ .0057	− .0032
46	Dalkeith..................	74 34.7	45 26.6	288	.6385	− .0095	− .0172
47	Vankleek Hill.............	74 38.6	45 31.0	296	.6434	− .0048	− .0148
48	....	74 43.9	45 25.5	240	.6597	+ .0145	+ .0063
49	Fassifern.................	74 40.6	45 21.3	327	.6343	+ .0037	− .0075
50	Fairview..................	74 43.6	45 20.0	308	.6351	+ .0046	− .0059

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Station No.	Station Name	Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
51	....	74° 46!7	45° 18!8	340 ft.	980.6372	+0.0115	−0.0001
52	....	74 54.0	45 20.7	220	.6485	+ .0087	+ .0012
53	Fournier........	74 52.3	45 26.8	217	.6440	− .0053	− .0127
54	Routhier........	74 47.6	45 28.6	215	.6541	+ .0019	− .0054
55	Marelan........	74 33.0	45 38.2	256	.6435	− .0193	− .0280
56	....	74 16.0	45 38.0	255	.6454	− .0172	− .0259
57	....	74 11.5	45 36.2	159	.6485	− .0204	− .0259
58	....	74 06.4	45 36.9	139	.6476	− .0242	− .0290
59	....	73 59.7	45 34.9	130	.6488	− .0209	− .0253
60	....	73 52.8	45 33.9	92	.6471	− .0246	− .0278
61	Rosemere........	73 47.8	45 38.0	89	980.6504	−0.0278	−0.0309
62	....	73 45.5	45 40.0	89	.6533	− .0279	− .0310
63	Terrebonne........	73 37.3	45 41.8	59	.6598	− .0270	− .0290
64	Charlemagne........	73 28.3	45 42.0	42	.6605	− .0296	− .0311
65	Repentigny........	73 25.4	45 45.7	38	.6663	− .0282	− .0295
66	St. Sulpice........	73 21.3	45 49.6	36	.6784	− .0222	− .0234
67	Pte. au Chêne........	74 45.0	45 38.7	187	.6710	+ .0010	− .0054
68	Montebello........	74 56.5	45 39.2	171	.6527	− .0196	− .0254
69	Buckingham Jct........	75 25.2	45 32.8	190	.6573	− .0035	− .0100
70	Powassan........	79 21.3	46 04.8	855	.6171	− .0294	− .0585
71	Black Rapids........	75 42.0	45 19.3	255	980.6256	−0.0088	−0.0175

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Station No.	Station Name	Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
1	Leitrim........	75° 32!2	45° 21!6	261 ft.	980.6268	−0.0106	−0.0194
2	....	75 33.4	45 21.1	270	.6264	− .0093	− .0185
3	....	75 34.7	45 20.5	289	.6256	− .0074	− .0173
4	Leitrim Rd. Jct........	75 36.0	45 19.9	345	.6242	− .0026	− .0144
5	....	75 38.0	45 19.0	338	.6246	− .0016	− .0131
6	....	75 42.6	45 15.7	284	.6181	− .0082	− .0179
7	Manotick........	75 41.1	45 13.6	275	.6204	− .0036	− .0130
8	....	75 44.0	45 18.2	298	.6203	− .0085	− .0186
9	....	75 44.5	45 19.0	314	.6138	− .0102	− .0209
10	....	75 43.6	45 20.3	287	.6208	− .0121	− .0219
11	....	75 44.3	45 21.5	311	980.6186	−0.0138	−0.0244
12	Ellwood........	75 39.9	45 22.2	288	.6250	− .0107	− .0205
13	....	75 38.6	45 21.2	310	.6239	− .0082	− .0188
14	....	75 36.3	45 20.2	319	.6249	− .0049	− .0158
15	....	75 36.5	45 19.6	322	.6264	− .0022	− .0132
16	....	75 37.1	45 19.4	315	.6270	− .0020	− .0127
17	South Gloucester........	75 34.3	45 16.8	336	.6231	+ .0000	− .0114
18	....	75 31.6	45 17.9	266	.6281	− .0032	− .0122
19	Edwards........	75 28.1	45 19.3	255	.6234	− .0110	− .0197
20	....	75 30.7	45 18.3	264	.6265	− .0056	− .0146
21	....	75 33.0	45 17.4	296	980.6270	−0.0008	−0.0108
22	Manotick Stn........	75 37.3	45 15.3	328	.6215	+ .0000	− .0112

C = 0.27714 mgals/div. PRINCIPAL FACTS FOR GRAVITY STATIONS, 1949 Atlas

Station No.	Station Name	Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
23	....	75° 38′.7	45° 18′.5	377 ft.	980.6220	+ .0003	− .0126
24	....	75 41.1	45 20.3	333	.6230	− .0056	− .0169
25	....	75 41.7	45 20.9	297	.6237	− .0092	− .0193

C = 0.27714 mgals/div. PRINCIPAL FACTS FOR GRAVITY STATIONS, 1951 Atlas

Station No.	Station Name	Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
1	....	75° 45′.7	45° 00′.2	314 ft.	980.5879	−0.0122	−0.0229
2	....	75 49.6	45 00.3	391	.5894	− .0037	− .0170
3	....	75 57.3	45 00.6	441	.5816	− .0072	− .0223
4	Kemptville P.O.	75 38.8	45 01.0	300	.5840	− .0185	− .0288
5	....	75 46.6	45 01.2	368	.5898	− .0068	− .0193
6	North Rideau	75 43.3	45 01.6	300	.5896	− .0140	− .0242
7	....	75 53.9	45 01.7	399	.5880	− .0064	− .0200
8	....	75 48.2	45 02.4	368	.5952	− .0032	− .0157
9	....	75 57.0	45 02.7	441	.5848	− .0072	− .0222
10	Beckett's Landing	75 41.9	45 02.8	302	.5912	− .0140	− .0243
11	....	75 33.8	45 02.9	338	980.5827	−0.0192	−0.0308
12	Marlmont Stn.	75 55.3	45 02.9	416	.5881	− .0065	− .0207
13	....	75 56.4	45 03.6	411	.5889	− .0073	− .0213
14	Hallville	75 31.2	45 03.7	288	.5873	− .0206	− .0304
15	....	75 59.3	45 03.9	408	.5855	− .0114	− .0253
16	....	75 59.8	45 04.5	436	.5833	− .0118	− .0267
17	....	75 36.2	45 05.6	294	.5941	− .0161	− .0261
18	....	75 31.2	45 07.1	264	.5959	− .0193	− .0283
19	....	75 34.7	45 07.7	305	.6005	− .0118	− .0222
20	Osgoode Stn.	75 36.7	45 08.6	303	.6094	− .0045	− .0148
21	Dalmeny	75 32.0	45 08.7	265	980.6012	−0.0163	−0.0253
22	....	75 34.9	45 11.1	306	.6120	− .0054	− .0158
23	Bray Stn.	75 37.4	45 11.5	298	.6142	− .0045	− .0146
24	....	75 33.5	45 14.5	312	.6197	− .0021	− .0127
25	Rosedale Stn.	75 56.3	44 54.4	367	.5841	− .0023	− .0148
26	Nolan's Corner	75 58.8	44 57.3	432	.5792	− .0055	− .0202
27	Burritt's Rapids	75 47.9	44 59.1	319	.5868	− .0112	− .0221
28	Nolan's Stn.	75 58.2	44 59.6	449	.5792	− .0073	− .0226
29	Russell	75 21.5	45 15.8	237	.6100	− .0208	− .0289
30	....	75 24.1	45 16.0	245	.6118	− .0187	− .0270
31	Embrum	75 17.1	45 16.3	224	980.6112	−0.0216	−0.0293
32	Mayerville	75 03.8	45 16.4	235	.6175	− .0145	− .0225
33	....	75 17.8	45 16.8	228	.6113	− .0220	− .0297
34	Pana	75 24.8	45 17.3	247	.6136	− .0186	− .0270
35	....	75 13.7	45 17.6	224	.6158	− .0190	− .0267
36	....	75 18.7	45 18.4	237	.6110	− .0238	− .0319
37	Casselman	75 05.2	45 18.7	218	.6206	− .0164	− .0238
38	....	75 07.2	45 19.1	215	.6200	− .0179	− .0252
39	Edwards	75 28.2	45 19.3	258	.6233	− .0108	− .0196
40	....	75 03.3	45 19.4	210	.6224	− .0164	− .0236

C = 0.27714 mgals/div. PRINCIPAL FACTS FOR GRAVITY STATIONS, 1951 Atlas

Station No.	Station Name	Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
41	....	75° 02!1	45° 19.7	206 ft.	980.6253	−0.0144	−0.0214
42	....	75 05.2	45 19.8	207	.6221	− .0176	− .0246
43	....	75 00.2	45 20.0	214	.6294	− .0094	− .0172
44	Limoges..................	75 15.3	45 20.3	234	.6132	− .0247	− .0327
45	....	75 22.1	45 20.8	256	.6168	− .0198	− .0285
46	Vars..................	75 21.1	45 21.2	252	.6172	− .0258	− .0290
47	....	75 00.9	45 21.4	207	.6275	− .0147	− .0217
48	....	75 05.0	45 21.7	222	.6237	− .0174	− .0250
49	Carlsbad Springs..................	75 28.7	45 22.4	227	.6320	− .0097	− .0175
50	....	75 16.2	45 22.5	225	.6167	− .0254	− .0331
51	Bearbrook Hall..................	75 19.9	45 23!3	217	980.6229	−0.0211	−0.0285
52	....	75 08.2	45 23.7	242	.6209	− .0214	− .0296
53	Navan..................	75 26.4	45 25.0	240	.6362	− .0083	− .0164
54	Leonard..................	75 21.2	45 25.4	272	.6303	− .0117	− .0210
55	Hammond..................	75° 14!5	45° 26!1	220	.6274	− .0205	− .0280
56	Bourget..................	75 10.2	45 26.4	215	.6247	− .0262	− .0315
57	....	75 26.5	45 26.9	293	.6359	− .0064	− .0164
58	Pendleton..................	75 03.7	45 27.8	232	.6248	− .0246	− .0325
59	....	75 22.4	45 27.8	288	.6362	− .0079	− .0178
60	....	75 14.7	45 28.1	271	.6276	− .0186	− .0279
61	....	75 27.3	45 28.3	291	.6401	−0.0045	−0.0145
62	....	75 14.1	45 30.1	282	.6288	− .0193	− .0289
63	....	75 23.8	45 30.1	317	.6425	− .0024	− .0132
64	....	75 05.5	45 30.4	263	.6291	− .0213	− .0302
65	Clarence Creek..................	75 13.1	45 30.4	219	.6345	− .0201	− .0275
66	....	75 12.1	45 30.8	178	.6376	− .0214	− .0275
67	....	75 05.8	45 31.2	270	.6295	− .0214	− .0306
68	Cumberland..................	75 24.7	45 31.2	193	.6532	− .0050	− .0116
69	....	75 06.2	45 31.8	276	.6297	− .0216	− .0310
70	....	75 06.8	45 32.8	183	.6375	− .0240	− .0303
71	Rockland..................	75 17.7	45 33.2	147	980.6503	−0.0152	−0.0202
72	Wendover..................	75 07.4	45 34.1	174	.6401	− .0242	− .0301
73	....	74 52.8	45 30.4	164	.6449	− .0148	− .0204
74	....	74 49.3	45 30.9	165	.6552	− .0051	− .0108
75	....	74 55.6	45 31.3	171	.6395	− .0209	− .0267
76	Alfred Stn..................	74 53.6	45 31.8	177	.6459	− .0147	− .0208
77	Caledonia Springs..................	74 48.0	45 32.7	165	.6592	− .0039	− .0095
78	....	74 59.3	45 32.9	273	.6330	− .0202	− .0295
79	Ritchance..................	74 48.3	45 33.6	169	.6591	− .0050	− .0107
80	....	74 59.7	45 33.7	279	.6342	− .0197	− .0292
81	....	74 48.3	45 35.1	167	980.6601	−0.0064	−0.0121
82	....	74 57.8	45 35.2	317	.6376	− .0150	− .0258
83	....	74 56.7	45 35.4	149	.6462	− .0224	− .0275
84	....	74 47.9	45 35.8	162	.6622	− .0058	− .0113
85	....	74 55.0	45 35.8	168	.6480	− .0194	− .0252
86	....	74 50.2	45 35.9	165	.6561	− .0118	− .0174
87	....	74 48.4	45 36.5	162	.6593	− .0097	− .0152
88	Alfred Centre Stn..................	74 52.7	45 36.5	169	.6509	− .0176	− .0233
89	Evantruel Stn..................	74 47.5	45 36.6	163	.6619	− .0072	− .0128
90	....	74 59.6	45 37.4	160	.6491	− .0215	− .0269

C = 0.27714 mgals/div. PRINCIPAL FACTS FOR GRAVITY STATIONS, 1951 Atlas

Station No.	Station Name	Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
91	Fassett	74° 52.′0	45° 38.′8	169 ft.	980.6556	−0.0163	−0.0220
92	Greenville Stn.	74 36.0	45 38.9	209	.6525	− .0157	− .0228
93	Calumet	74 38.3	45 38.9	195	.6591	− .0106	− .0171

C = 0.2315 mgals/div. PRINCIPAL FACTS FOR GRAVITY STATIONS, 1951 North American 85

Station No.	Station Name	Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
1		75° 38.′9	45° 14.′7	313 ft.	980.6207	−0.0014	−0.0120
2		75 38.3	45 13.7	318	.6194	− .0007	− .0115
3		75 39.8	45 13.1	289	.6204	− .0015	− .0114
4		75 43.0	45 13.1	329	.6139	− .0043	− .0155
5		75 44.6	45 12.4	310	.6137	− .0052	− .0157
6		75 46.0	45 11.0	305	.6120	− .0066	− .0170
7		75 47.3	45 11.3	306	.6102	− .0074	− .0178
8		75 49.1	45 11.8	307	.6093	− .0090	− .0194
9		75 48.9	45 14.5	310	.6074	− .0146	− .0252
10		75 47.0	45 14.1	347	.6098	− .0082	− .0200
11		75 46.4	45 13.0	314	980.6105	−0.0089	−0.0196
12		75 45.0	45 13.6	322	.6117	− .0079	− .0188
13		75 43.6	45 14.2	311	.6137	− .0078	− .0184
14		75 40.8	45 11.4	309	.6148	− .0027	− .0132
15		75 39.9	45 10.5	320	.6124	− .0027	− .0136
16		75 39.2	45 9.4	296	.6125	− .0032	− .0133
17		75 40.3	45 9.1	286	.6121	− .0041	− .0138
18		75 39.6	45 6.7	293	.6139	− .0026	− .0126
19		75 41.9	45 7.1	306	.6084	− .0029	− .0133
20		75 40.5	45 7.5	313	.6090	− .0022	− .0129
21		75 39.6	45 6.7	293	980.6032	−0.0087	−0.0187
22		75 39.4	45 5.0	289	.5925	− .0172	− .0271
23		75 40.0	45 3.8	289	.5910	− .0169	− .0268
24		75 39.2	45 1.2	317	.5856	− .0158	− .0266
25		75 39.9	45 2.0	301	.5894	− .0147	− .0249
26		75 43.8	45 4.1	315	.5999	− .0060	− .0168
27		75 45.5	45 4.3	338	.6004	− .0037	− .0152
28	Pierce's Corners	75 45.5	45 5.5	321	.6040	− .0035	− .0144
29		75 46.2	45 6.1	310	.6056	− .0038	− .0144
30	Stittsville	75 55.3	45 15.6	399	.5982	− .0171	− .0307
31	Stanley Corners	75 54.3	45 14.1	408	980.5969	−0.0153	−0.0292
32		75 56.7	45 12.7	408	.5962	− .0139	− .0278
33		75 58.4	45 11.6	447	.5940	− .0108	− .0260
34		75 57.7	45 11.0	412	.5967	− .0105	− .0245
35	Munster	75 56.4	45 9.9	414	.5942	− .0111	− .0252
36		75 55.3	45 11.5	374	.5994	− .0121	− .0249
37		75 53.0	45 12.9	339	.6028	− .0141	− .0257
38	Richmond Stn.	75 49.4	45 11.2	311	.6083	− .0087	− .0193
39		75 51.5	45 10.9	323	.6064	− .0090	− .0200
40		75 53.2	45 9.8	343	.6015	− .0104	− .0221

C = 0.2315 mgals/div. PRINCIPAL FACTS FOR GRAVITY BASES, 1951 **North American 85**

Station No.	Station Name	Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
41	....	75° 55.0	45 8.7	359 ft.	980.5977	− .0110	−0.0232
42	....	75 53.5	45 7.4	336	.5987	− .0102	− .0217
43	Dwyer Hill..........................	75 56.6	45 7.6	376	.5939	− .0116	− .0244
44	Hall................................	75 55.4	45 6.4	383	.5932	− .0098	− .0228
45	Droger Hill (Stn.)..................	75 54.0	45 5.0	370	.5949	− .0072	− .0198
46	Maple Hill..........................	75 52.3	45 2.5	391	.5917	− .0047	− .0180
47	....	75 51.0	45 3.3	371	.5952	− .0043	− .0169
48	....	75 49.7	45 5.2	338	.5991	− .0063	− .0178
49	....	75 47.4	45 7.2	316	.6063	− .0042	− .0150
50	....	75 48.6	45 8.2	320	.6053	− .0063	− .0172
51	....	75 46.7	45° 9.3	318	980.6084	−0.0051	−0.0159
52	....	75 44.7	45 9.2	313	.6106	− .0032	− .0139
53	....	75 46.1	45 10.4	317	.6106	− .0046	− .0154
54	....	75 32.8	44 57.1	330	.5737	− .0203	− .0315
55	....	75 36.8	44 56.3	356	.5679	− .0224	− .0346
56	....	75 38.3	44 57.4	332	.5714	− .0229	− .0342
57	....	75 37.9	44 53.2	346	.5681	− .0185	− .0303
58	....	75 41.3	44 54.3	333	.5647	− .0248	− .0361
59	....	75 42.0	44 58.5	339	.5789	− .0163	− .0279
60	Burritt R.R.........................	75 46.3	44 56.5	368	.5777	− .0118	− .0243
61	....	75 53.3	44 57.4	386	980.5868	−0.0024	−0.0155
62	....	75 48.5	44 51.9	392	.5667	− .0136	− .0270
63	....	75 44.2	44 53.2	367	.5620	− .0226	− .0351
64	....	75 44.6	44 50.2	369	.5590	− .0209	− .0335
65	....	75 47.5	44 48.0	377	.5617	− .0142	− .0270
66	....	75 49.0	44 49.9	385	.5668	− .0112	− .0243
67	Easton..............................	75 53.1	44 50.2	369	.5733	− .0066	− .0192
68	Jasper..............................	75 56.0	44 49.9	342	.5746	− .0046	− .0162
69	....	75 57.9	44 51.4	343	.5743	− .0099	− .0216
70	....	75 52.1	44 52.1	349	.5734	− .0113	− .0232
71	Newbliss............................	75 58.4	44 47.6	409	980.5644	−0.0079	−0.0218
72	....	75 54.3	44 47.5	360	.5691	− .0076	− .0199
73	Yule................................	75 51.6	44 46.6	398	.5632	− .0086	− .0022
74	....	75 56.9	44 43.7	409	.5601	− .0063	− .0202
75	Toledo..............................	75 59.7	44 44.4	396	.5608	− .0079	− .0214
76	....	75 54.9	44 40.6	416	.5508	− .0103	− .0244
77	....	75 39.9	44 37.6	394	.5420	− .0166	− .0301
78	Maitland............................	75 37.1	44 38.4	327	.5504	− .0157	− .0269
79	....	75 37.4	44 41.1	336	.5517	− .0177	− .0291
80	....	75 35.3	44 42.8	353	.5561	− .0142	− .0262
81	....	75 32.5	44 44.6	320	980.5672	−0.0089	−0.0198
82	....	75 36.0	44 45.5	316	.5615	− .0164	− .0271
83	....	75 31.7	44 47.1	302	.5718	− .0098	− .0201
84	Roebuck.............................	75 36.4	44 48.2	336	.5641	− .0156	− .0274
85	....	75 38.5	44 47.2	331	.5612	− .0178	− .0291
86	....	75 39.1	44 50.4	345	.5626	− .0199	− .0316
87	....	75 42.3	44 48.9	332	.5586	− .0229	− .0342
88	North Augusta.......................	75 44.4	44 45.7	335	.5543	− .0221	− .0335
89	....	75 42.6	44 43.8	386	.5454	− .0233	− .0365
90	Algonquin...........................	75 40.2	44 42.2	354	.5515	− .0178	− .0299

C=0.2315 mgals/div. PRINCIPAL FACTS FOR GRAVITY STATIONS, 1951 North American 85

Station No.	Station Name	Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
91	....	75° 39.'3	44° 43.'3	340 ft.	980.5541	−0.0182	−0.0298
92	....	75 39.8	44 39.3	385	.5442	− .0178	− .0310
93	....	75 43.7	44 36.6	366	.5417	− .0181	− .0305
94	....	75 46.7	44 36.1	370	.5377	− .0209	− .0335
95	....	75 46.7	44 37.5	387	.5384	− .0207	− .0339
96	....	75 49.3	44 39.3	393	.5451	− .0162	− .0296
97	Greenbush..................	75 50.8	44 41.3	400	.5483	− .0153	− .0290
98	....	75 52.4	44 43.4	430	.5548	− .0092	− .0238
99	....	75 49.7	44 45.3	389	.5564	− .0143	− .0275
100	Jelly Stn..................	75 48.8	44 44.1	376	.5517	− .0184	− .0312
101	Bellamy....................	75 47.6	44 42.3	397	980.5446	−0.0190	−0.0325
102	Hawkins....................	75 46.3	44 41.3	393	.5441	− .0202	− .0336
103	Fairfield..................	75 44.0	44 39.4	398	.5431	− .0179	− .0314
104	....	75 49.8	44 37.3	402	.5438	− .0136	− .0273
105	Forthton Stn...............	75 51.7	44 38.4	410	.5459	− .0124	− .0264
106	Glen Elbe..................	75 53.5	44 38.4	370	.5483	− .0138	− .0264
107	....	75 58.0	44 40.7	430	.5509	− .0090	− .0237
108	Athens.....................	75 57.3	44 37.8	417	.5452	− .0116	− .0258
109	....	75 55.3	44 35.5	411	.5420	− .0119	− .0259
110	....	75 58.2	44 34.6	316	.5494	− .0121	− .0228
111	....	75 54.0	44 34.8	402	980.5411	−0.0126	−0.0263
112	....	75 51.4	44 32.6	432	.5339	− .0136	− .0283
113	....	75 49.7	44 34.6	361	.5397	− .0175	− .0298
114	Lyn Jct....................	75 46.1	44 34.1	282	.5425	− .0207	− .0306
115	....	75 45.2	44 32.7	303	.5416	− .0182	− .0285
116	....	75 48.5	44 30.2	268	.5383	− .0210	− .0302
117	Mallorytown................	75 53.2	44 28.8	334	.5346	− .0164	− .0278
118	....	75 55.5	44 27.3	371	.5326	− .0127	− .0253
119	La Rue Mills...............	75 53.0	44 26.1	326	.5296	− .0181	− .0292
120	Rockport...................	75 56.3	44 22.9	290	.5236	− .0227	− .0326
121	Mitchelville...............	75 58.7	44 25.0	307	980.5283	−0.0196	−0.0300
122	....	75 59.4	44 28.0	353	.5328	− .0152	− .0273
123	....	75 56.8	44 41.7	339	.5402	− .0147	− .0263
124	....	75 55.0	44 30.4	423	.5335	− .0116	− .0260
125	....	75 28.3	44 44.1	256	.5740	− .0074	− .0161
126	....	75 29.9	44 48.0	291	.5736	− .0103	− .0202
127	Spencerville...............	75 33.8	44 49.9	319	.5697	− .0145	− .0254
128	....	75 29.3	44 52.9	280	.5816	− .0108	− .0203
129	....	75 30.0	44 55.4	277	.5803	− .0161	− .0256
130	Groveton Stn...............	75 35.3	44 52.6	339	.5714	− .0150	− .0266
131	South Gower................	75 33.2	44 59.8	326	980.5783	−0.0201	−0.0312
132	....	75 28.6	45 00.5	297	.5830	− .0192	− .0293
133	Mountain...................	75 29.8	45 02.0	273	.5855	− .0212	− .0305
134	Inkerman Stn...............	75 24.6	45 03.7	266	.5908	− .0192	− .0282
135	....	75 24.2	45 07.0	238	.5962	− .0213	− .0294
136	....	75 31.8	45 11.4	277	.6102	− .0102	− .0197
137	....	75 28.2	45 10.5	253	.6025	− .0189	− .0275
138	....	75 25.4	45 11.6	248	.6030	− .0205	− .0289
139	....	75 24.3	45 09.7	240	.6002	− .0212	− .0294
140	Marionville................	75 21.4	45 10.9	266	.6029	− .0179	− .0269

C=0.2315 mgals/div. PRINCIPAL FACTS FOR GRAVITY STATIONS, 1951 North American 85

Station No.	Station Name	Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
141	Marvelville	75° 22'.5	45° 12'.9	233 ft.	980.6060	−0.0209	−0.0288
142		75 27.1	45 14.7	277	.6123	− .0131	− .0226
143	Metcalfe	75 28.4	45 14.1	278	.6133	− .0111	− .0206
144		75 29.8	45 13.6	284	.6138	− .0094	− .0191
145		75 16.2	45 13.7	227	.6076	− .0210	− .0288
146	Cambridge	75 13.3	45 14.6	226	.6113	− .0188	− .0265
147	St. Albert	75 11.7	45 14.1	224	.6114	− .0181	− .0258
148		75 08.5	45 15.9	194	.6148	− .0202	− .0269
149	Crysler	75 09.4	45 12.6	223	.6111	− .0163	− .0239
150		75 10.7	45 12.3	236	.6097	+ .0160	− .0240
151		75 12.3	45 11.8	244	980.6098	−0.0143	−0.0227
152		75 14.3	45 11.1	256	.6096	− .0124	− .0211
153	Morewood	75 17.1	45 10.6	254	.6053	− .0261	− .0348
154		75 18.6	45 11.9	228	.6073	− .0185	− .0263
155		75 16.5	45 10.0	243	.6069	− .0146	− .0229
156		75 18.6	45 08.2	248	.6034	− .0150	− .0234
157		75 20.4	45 04.4	246	.5993	− .0136	− .0219
158		75 15.6	45 06.1	240	.6063	− .0097	− .0179
159	Chesterville	75 13.9	45 06.4	240	.6097	+ .0067	− .0149
160		75 10.7	45 06.9	229	.6106	− .0077	− .0155
161	Goldfield	75 08.1	45 07.5	257	980.6146	−0.0019	−0.0107
162		75 09.5	45 09.4	226	.6109	− .0113	− .0190
163	Berwick	75 06.7	45 10.5	245	.6132	− .0090	− .0173
164	Glenpayne	75 05.5	45 12.6	249	.6133	− .0117	− .0202
165	Finch	75 05.2	45 08.7	276	.6190	+ .0025	− .0069
166		75 02.7	45 09.5	280	.6210	+ .0036	− .0059
167	Newington	75 00.7	45 07.2	323	.6210	+ .0112	+ .0002
168		75 02.4	45 05.2	320	.6185	+ .0114	+ .0005
169		75 05.8	45 03.5	308	.6176	+ .0119	+ .0014
170		75 06.7	45 05.9	299	.6162	+ .0060	− .0042
171	Grantley	75 09.0	45 04.5	288	980.6121	+0.0030	−0.0068
172		75 09.5	45 02.6	293	.6115	+ .0058	− .0042
173		75 11.2	45 02.0	282	.6081	+ .0022	− .0074
174		75 12.8	45 01.4	282	.6059	+ .0009	− .0087
175		75 15.0	45 03.8	239	.6040	− .0086	− .0168
176	Elma	75 14.4	45 00.8	258	.6048	− .0015	− .0103
177		75 15.8	45 00.2	248	.6035	− .0029	− .0113
178	Winchester Springs	75 17.6	45 01.9	245	.6019	− .0074	− .0157
179		75 19.6	45 03.4	250	.5999	− .0111	− .0196
180		75 22.8	45 00.7	238	.5984	− .0096	− .0177
181		75 21.7	44 59.0	227	980.6003	−0.0062	−0.0140
182		75 23.2	45 55.7	239	.5933	− .0071	− .0153
183		75 26.4	44 57.0	265	.5872	− .0128	− .0218
184		25 25.4	44 54.8	254	.5893	− .0084	− .0171
185		75 27.2	44 49.5	276	.5786	− .0090	− .0184
186		75 24.3	44 51.3	262	.5866	− .0050	− .0139
187		75 20.9	44 52.7	265	.5925	− .0010	+ .0100
188	Iroquois	75 18.3	44 50.8	245	.5939	+ .0013	− .0070
189	Cardinal	75 23.3	44 47.8	279	.5834	− .0014	− .0109
190		75 14.6	44 52.7	250	.5993	+ .0044	− .0041

C=0.2315 mgals/div. PRINCIPAL FACTS FOR GRAVITY STATIONS, 1951 North American 85

Station No.	Station Name	Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
191	Rowena	75° 16!9	44° 54!4	287 ft.	980.5974	+0.0034	−0.0064
192		75 18.5	44 57.7	266	.5988	− .0021	− .0111
193	Williamsburg	75 14.8	44 58.5	275	.6028	+ .0016	− .0078
194	Glen Becker	75 12.7	44 56.1	280	.6071	+ .0099	+ .0004
195	Riverside	75 08.0	44 55.3	237	.6126	+ .0126	+ .0045
196		75 09.3	44 58.9	268	.6138	+ .0113	+ .0022
197	Hoasic	75 07.7	45 00.2	285	.6172	+ .0143	+ .0046
198		75 03.8	45 01.0	288	.6178	+ .0140	+ .0042
199		75 02.4	44 57.7	248	.6168	+ .0142	+ .0058
200	Nudell Bush	75 05.8	44 57.7	262	.6143	+ .0133	+ .0046
201	Crysler's Farm (Monument)	75 05.9	44 55.8	288	980.6143	+0.0133	+0.0053
202	Farran's Point	75 00.3	44 59.1	242	.6181	+ .0129	+ .0046
203	Osnabruck Centre	75 00.4	45 02.0	280	.6194	+ .0133	+ .0038
204	Lunenburg	74 57.3	45 03.1	282	.6181	+ .0105	+ .0009
205	Wales	74 55.3	45 00.6	238	.6149	+ .0070	− .0011
206	Moulinette	74 51.4	45 01.7	233	.6145	+ .0044	− .0035
207	Mille Roches	74 49.8	45 01.7	223	.6149	+ .0039	− .0037
208		74 50.8	45 03.8	255	.6167	+ .0056	− .0031
209		74 49.5	45 03.4	217	.6181	+ .0040	− .0034
210		74 48.5	45 03.4	208	.6184	+ .0035	− .0036
211	Cornwall Centre	74 47.5	45 03.1	207	980.6184	+0.0038	−0.0033
212		74 45.8	45 02.4	201	.6184	+ .0043	− .0025
213	Uscan	74 44.5	45 00.0	198	.6166	+ .0058	− .0009
214		74 48.5	45 05.2	235	.6218	+ .0067	− .0013
215		74 51.5	45 05.1	253	.6194	+ .0061	+ .0025
216	Harrison Corners	74 54.3	45 05.1	292	.6195	+ .0099	− .0001
217	Northfield	74 55.7	45 07.4	352	.6206	+ .0132	+ .0012
218	Northfield Stn.	74 57.2	45 06.3	334	.6209	+ .0134	+ .0020
219		74 57.1	45 09.3	334	.6247	+ .0127	+ .0013
220		74 58.8	45 11.4	330	.6223	+ .0068	− .0044
221		75 02.6	45 13.0	288	980.6151	−0.0068	−0.0166
222		75 03.4	45 14.0	241	.6165	− .0113	− .0195
223		75 02.3	45 14.5	237	.6189	− .0100	− .0181
224	Moose Creek	74 57.8	45 15.3	290	.6261	+ .0010	− .0089
225		74 58.5	45 13.5	309	.6222	+ .0016	− .0090
226		74 57.4	45 12.1	331	.6236	+ .0071	− .0041
227	Monkland	74 52.5	45 11.8	333	.6234	+ .0076	− .0037
228	McMillan Corners	74 51.4	45 09.7	319	.6234	+ .0094	− .0015
229		74 50.7	45 09.0	278	.6254	+ .0087	− .0008
230	Bonville	74 49.5	45 07.6	285	.6228	+ .0088	− .0009
231	Graveyard Pt.	74 38.3	45 02.0	177	980.6214	+0.0057	−0.0004
232	Summerstown	74 33.2	45 03.6	159	.6276	+ .0078	+ .0023
233	Summerstown Stn.	74 35.8	45 05.5	182	.6271	+ .0065	+ .0003
234		74 36.9	45 06.8	192	.6291	+ .0076	+ .0010
235	Glendale	74 34.8	45 08.1	170	.6327	+ .0071	+ .0013
236	Glen Gordon Stn.	74 31.7	45 10.7	178	.6374	+ .0086	+ .0026
237		74 33.3	45 10.2	189	.6358	+ .0089	+ .0024
238		74 30.4	45 11.2	185	.6387	+ .0099	+ .0036
239		74 32.5	45 11.5	186	.6375	+ .0083	+ .0020
240		74 33.4	45 12.6	220	.6360	+ .0083	+ .0008

C=0.2315 mgals/div. PRINCIPAL FACTS FOR GRAVITY STATIONS, 1951 **North American 85**

Station No.	Station Name	Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
241		74° 34'.1	45° 13'.4	240 ft.	980.6357	+0.0087	+0.0005
242		74 35.0	45 14.4	251	.6351	+ .0076	+ .0009
243		74 35.5	45 15.2	236	.6364	+ .0063	− .0017
244		74 36.4	45 16.2	295	.6338	+ .0078	− .0023
245		74 37.2	45 17.2	281	.6349	+ .0060	− .0035
246		74 41.2	45 17.1	298	.6306	+ .0035	− .0066
247		74 44.6	45 15.4	334	.6274	+ .0062	− .0052
248		74 47.4	45 14.6	354	.6276	+ .0095	− .0026
249		74 48.0	45 15.3	326	.6310	+ .0093	− .0018
250		74 47.0	45 14.2	310	.6287	+ .0071	− .0035
251	Apple Hill	74 46.1	45 13.1	301	980.6265	+0.0057	−0.0045
252		74 47.4	45 12.8	308	.6260	+ .0063	− .0042
253		74 49.5	45 12.4	326	.6252	+ .0078	− .0033
254		74 52.7	45 13.9	386	.6249	+ .0109	− .0022
255		74 46.3	45 09.9	275	.6271	+ .0087	− .0007
256		74 46.8	45 12.0	288	.6262	+ .0059	− .0039
257		74 46.6	45 11.7	279	.6266	+ .0058	− .0037
258		74 41.1	45 12.0	247	.6306	+ .0064	− .0020
259		74 40.8	45 11.6	224	.6326	+ .0069	− .0008
260		74 39.4	45 09.9	238	.6313	+ .0094	+ .0013
261		74 37.9	45 07.8	172	980.6327	+0.0078	+0.0019
262		74 38.2	45 05.9	197	.6267	+ .0069	+ .0002
263		74 39.5	45 04.8	193	.6249	+ .0065	− .0001
264		74 40.5	45 04.3	176	.6240	+ .0047	− .0013
265		74 41.5	45 03.8	183	.6221	+ .0042	− .0020
266		74 41.9	45 06.1	219	.6234	+ .0054	− .0021
267		74 43.5	45 08.3	208	.6280	+ .0057	− .0014
268		74 37.3	45 11.9	253	.6320	− .0014	− .0001
269		74 35.5	45 09.7	188	.6357	+ .0094	+ .0030
270	Glenroy	74 39.1	45 14.5	271	.6314	+ .0057	− .0035
271	Glen Norman Stn.	74 31.7	45 16.7	253	980.6405	+0.0098	+0.0012
272		74 29.7	45 17.3	252	.6421	+ .0104	+ .0018
273	Dalhousie Stn.	74 27.3	45 17.9	225	.6446	+ .0095	+ .0018
247	Glen Robertson	74 30.2	45 21.6	257	.6436	+ .0059	− .0029
275		74 34.6	45 19.7	260	.6406	+ .0061	− .0028
276	Fassifern	74 40.6	45 21.3	326	.6347	+ .0040	− .0071
277	Fairview	74 43.6	45 20.0	308	.6356	+ .0051	− .0054
278	Greenfield	74 46.1	45 18.0	340	.6348	+ .0103	− .0013
279	Maxville	74 51.5	45 17.2	336	.6358	+ .0121	+ .0007
280	Tayside	74 57.6	45 17.7	268	.6306	− .0002	− .0093
281	Sandringham	74 56.2	45 18.4	307	980.6335	+0.0054	−0.0051
282		74 57.2	45 20.0	216	.6355	− .0037	− .0110
283		74 55.4	45 20.6	215	.6441	+ .0039	− .0034
284		74 54.0	45 20.7	220	.6485	+ .0087	+ .0012
285		74 50.1	45 22.9	229	.6560	+ .0137	+ .0059
286		74 48.3	45 20.8	276	.6499	+ .0152	+ .0058
287		74 45.2	45 22.1	327	.6443	+ .0125	+ .0013
288	Laggan	74 42.3	45 23.4	279	.6499	+ .0115	+ .0020
289	McCrimmon	74 44.0	45 25.4	240	.6599	+ .0149	+ .0067
290		74 47.0	45 24.1	236	.6576	+ .0141	+ .0061

C=0.2315 mgals/div. PRINCIPAL FACTS FOR GRAVITY STATIONS, 1951 North American 85

Station No.	Station Name	Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
291	St. Isidore	74° 54!4	45° 23!1	207 ft.	980.6465	+0.0019	−0.0052
292		74 56.6	45 22.6	204	.6388	− .0054	− .0124
293	Rose Corner	74 58.7	45 22.0	209	.6316	− .0112	− .0184
294		74 55.9	45 26.1	216	.6341	− .0143	− .0216
295	Lalonde	74 56.9	45 28.1	169	.6338	− .0220	− .0278
296		74 54.4	54 26.5	213	.6384	− .0109	− .0181
297		74 51.0	45 25.5	210	.6524	+ .0044	− .0028
298	Routhier	74 47.6	45 28.6	215	.6540	+ .0018	− .0055
299		74 49.5	45 27.9	213	.6510	− .0004	− .0076
300		74 45.1	45 29.6	210	.6562	+ .0021	− .0051
301		74 43.9	45 30.6	222	980.6571	+0.0026	−0.0050
302		74 42.2	45 31.3	208	.6558	− .0011	− .0082
303		74 41.1	45 33.6	234	.6557	− .0022	− .0102
304		74 42.4	45 35.7	208	.6629	− .0006	− .0077
305		74 38.9	45 30.0	321	.6425	− .0018	− .0127
306		74 37.5	45 28.2	280	.6404	− .0051	− .0146
307		74 40.7	45 26.8	218	.6550	+ .0058	− .0016
308	Lochiel	74 37.4	45 22.7	285	.6361	− .0006	− .0103
309		74 37.5	45 25.4	224	.6433	− .0032	− .0109
310	Dalkeith	74 34.7	45 26.6	229	.6389	− .0090	− .0168
311	Glen Sandfield	74 32.0	45 24.3	237	980.6440	+0.0003	−0.0078
312		74 35.2	45 27.7	256	.6375	− .0094	− .0182
313		74 37.1	45 35.3	233	.6510	− .0096	− .0175
314		74 33.1	45 28.6	255	.6384	− .0100	− .0187
315		74 32.5	45 29.9	251	.6396	− .0112	− .0197
316		74 31.9	45 31.3	259	.6408	− .0113	− .0202
317		74 31.6	45 32.0	253	.6422	− .0115	− .0201
318		74 30.7	45 33.1	239	.6436	− .0131	− .0213
319		74 30.6	45 34.1	227	.6449	− .0144	− .0222
320		74 31.6	45 33.9	248	.6439	− .0132	− .0216
321	Stardale Stn.	74 33.6	45 31.7	289	980.6406	−0.0093	−0.0192
322		74 35.0	45 32.5	241	.6456	− .0102	− .0184
323	Grenville Stn.	74 36.0	45 38.9	206	.6528	− .0157	− .0227
324		74 34.2	45 39.3	357	.6400	− .0149	− .0271
325		74 33.4	45 39.9	367	.6368	− .0181	− .0306
326	Rawcliffe	74 33.1	45 41.1	535	.6267	− .0142	− .0324
327		74 32.8	45 41.9	717	.6188	− .0062	− .0306
328		74 33.0	45 42.7	748	.6245	+ .0013	− .0242
329		74 30.4	45 41.5	766	.6121	− .0076	− .0337
330		74 31.2	45 38.2	288	.6375	− .0225	− .0322
331		74 31.5	45 36.6	171	980.6491	−0.0193	−0.0251
332		74 52.2	45 33.7	186	.6482	− .0142	− .0206

C=0.1117 mgals/div. PRINCIPAL FACTS FOR GRAVITY STATIONS, 1951 Worden 44

Station No.	Station Name	Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
1	Laurentian Air Service..........	75° 40'.7	45° 27'.4	190 ft.	980.6353	−0.0174	−0.0239
2	Madawaska L..........	78 24.0	45 17.7	1401	.5294	+ .0052	− .0425
3	Big Trout L..........	78 38.1	45 46.1	1323	.5752	+ .0009	− .0441

C=0.1117 mgals/div. PRINCIPAL FACTS FOR GRAVITY STATIONS, 1952 Worden 44

(Elevations followed by A are by Altimeter)

Station No.	Station Name	Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
1	Bainsville..........	74° 24'.9	45° 11'.0	173 ft.	980.6416	+0.0120	+0.0061
2	....	74 28.5	45 12.6	179	.6409	+ .0093	+ .0032
3	....	74 26.6	45 13.3	178	.6427	+ .0100	+ .0040
4	River Baudette..........	74 19.7	45 13.6	166	.6458	+ .0115	+ .0059
5	....	74 20.3	45 14.2	170	.6460	+ .0112	+ .0054
6	....	74 27.2	45 14.5	190	.6437	+ .0104	+ .0039
7	....	74 25.6	45 15.2	193	.6442	+ .0101	+ .0035
8	....	74 11.8	45 15.8	164	.6463	+ .0085	+ .0029
9	....	74 24.1	45 16.1	190	.6456	+ .0099	+ .0034
10	....	74 26.4	45 16.2	206	.6444	+ .0100	+ .0030
11	Coteau Stn..........	74 13.8	45 16.6	157	980.6477	+0.0081	+0.0027
12	....	74 19.4	45 17.5	176	.6469	+ .0078	+ .0018
13	Laberge Stn..........	74 23.7	45 17.9	209	.6455	+ .0089	+ .0017
14	....	74 15.2	45 17.9	159	.6471	+ .0058	+ .0003
15	Wilsonvale Stn..........	74 11.0	45 18.1	161	.6458	+ .0043	− .0011
16	St. Polycarpe..........	74 17.7	45 18.2	175	.6468	+ .0065	+ .0005
17	St. Telesphore Stn..........	74 24.1	45 18.6	209	.6456	+ .0079	+ .0007
18	....	74 9.4	45 18.9	160	.6449	+ .0021	− .0033
19	....	74 18.2	45 19.1	179	.6454	+ .0041	− .0020
20	....	74 0.5	45 19.5	144	.6432	− .0020	− .0069
21	De Beaujeu Stn..........	74 20.1	45 19.6	195	980.6454	+0.0048	−0.0018
22	....	74 4.5	45 19.6	150	.6448	+ .0	− .0051
23	Pont Chateau..........	74 12.3	45 19.7	168A	.6461	+ .0029	+ .0028
24	St. Dominique..........	74 7.6	45 19.8	154	.6448	+ .0001	− .0052
25	Cote St. Emmanuel..........	74 10.8	45 20.7	164	.6451	+ .0	− .0056
26	Cedars Stn..........	74 5.4	45 20.8	157	.6450	− .0009	+ .0063
27	St. Clet..........	74 13.2	45 21.1	176	.6447	+ .0002	− .0058
28	St. Justine Stn..........	74 25.3	45 21.3	246	.6454	+ .0071	− .0012
29	....	74 9.0	45 21.4	164	.6457	− .0005	− .0061
30	Beauvoir..........	74 18.5	45 21.8	207A	.6451	+ .0024	− .0047
31	....	74 21.1	45 21.9	209A	980.6460	+0.0034	−0.0038
32	....	74 28.2	45 22.4	233	.6447	+ .0035	− .0044
33	....	74 14.9	45 22.7	198A	.6444	− .0005	− .0072
34	St. Lazare Stn..........	74 6.3	45 22.8	163	.6470	− .0014	− .0069
35	....	74 10.0	45 22.8	250	.6414	+ .0012	− .0073
36	....	74 3.8	45 23.0	123	.6499	− .0025	− .0067
37	Ste. Marie de Ste. Marthe..........	74 18.2	45 23.1	194	.6467	+ .0008	− .0058
38	Dorion-Vaudreuil..........	74 0.7	45 23.2	82	.6498	− .0068	− .0096
39	....	74 21.2	45 23.5	215	.6444	− .0002	− .0075
40	....	74 23.6	45 24.0	299	.6419	+ .0045	− .0057

C=0.1117 mgals/div. PRINCIPAL FACTS FOR GRAVITY STATIONS, 1952 Worden 44

Station		Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies	
No.	Name					Free Air	Bouguer
41		74° 25.'4	45° 24.'3	226 ft.	980.6468	+0.0021	−0.0056
42		74 6.8	45 24.3	171	.6461	− .0038	− .0096
43		74 11.2	45 24.3	326	.6383	+ .0030	− .0081
44	Ste. Marthe	74 17.7	45 24.4	202	.6461	− .0010	− .0079
45		74 29.7	45 24.6	226	.6458	+ .0007	− .0070
46		74 13.5	45 24.6	363	.6371	+ .0048	− .0075
47		74 20.8	45 24.8	230	.6467	+ .0016	− .0062
48		74 14.8	45 25.3	195	.6451	− .0041	− .0107
49		74 7.8	45 25.3	216	.6440	− .0032	− .0105
50		74 17.4	45 25.6	363	.6298	− .0040	− .0163
51		74 6.7	45 25.9	118	980.6497	−0.0076	−0.0116
52		74 6.0	45 26.2	86	.6523	− .0084	− .0113
53		74 21.0	45 26.5	355	.6343	− .0015	− .0136
54	Ste. Anne de Prescott	74 28.3	45 26.6	220	.6454	− .0033	− .0108
55		74 19.9	45 26.7	452	.6233	− .0038	− .0192
56		74 10.1	45 26.8	174	.6440	− .0093	− .0153
57		74 20.3	45 27.5	414	.6258	− .0061	− .0202
58	Oka	74 5.4	45 27.6	81	.6512	− .0121	− .0148
59	Cherrier	74 25.8	45 27.7	190	.6459	− .0073	− .0138
60	Hudson Heights	74 9.1	45 27.9	88	.6442	− .0189	− .0219
61		74 20.6	45 28.1	174	980.6368	−0.0185	−0.0245
62	Choisy Stn.	74 13.1	45 28.5	104	.6406	− .0219	− .0255
63	Rigaud	74 18.1	45 28.9	103	.6383	− .0249	− .0284
64		74 21.4	45 29.4	144	.6423	− .0178	− .0227
65		74 7.9	45 29.4	87[A]	.6464	− .0190	− .0220
66		74 24.9	45 29.6	157	.6438	− .0153	− .0207
67	La Trappe	74 1.9	45 29.6	282	.6417	− .0057	− .0153
68		74 26.7	45 29.9	180	.6440	− .0135	− .0196
69	St. Eugene	74 27.8	45 30.1	180	.6444	− .0134	− .0195
70		74 03.5	45 30.6	353[A]	.6415	− .0007	− .0127
71		74 9.5	45 30.8	99[A]	980.6450	−0.0214	−0.0248
72		74 27.9	45 31.2	184	.6447	− .0143	− .0206
73		74 22.0	45 31.4	93	.6447	− .0232	− .0263
74		74 13.5	45 31.6	98	.6462	− .0215	− .0248
75		74 5.0	45 31.7	234	.6400	− .0151	− .0231
76		74 19.9	45 32.2	81	.6460	− .0242	− .0269
77		74 27.5	45 32.3	189	.6457	− .0145	− .0210
78		74 6.4	45 32.8	165	.6410	− .0222	− .0278
79		74 9.0	45 32.9	186	.6374	− .0240	− .0303
80	Côte St. Etienne	74 7.8	45 33.7	150	.6416	− .0244	− .0295
81	St. Andrews East	74 20.0	45 33.8	109	980.6467	−0.0232	−0.0270
82	Pt. Fortune	74 23.1	45 33.8	119	.6461	− .0229	− .0270
83		74 17.7	45 34.3	118	.6478	− .0261	− .0261
84		74 26.7	45 34.3	112	.6504	− .0201	− .0239
85	St. Placide Stn.	74 10.2	45 34.3	156	.6453	− .0210	− .0263
86	St. Benoit	74 5.7	45 34.4	153	.6455	− .0212	− .0264
87	Lalande Stn.	74 14.3	45 34.6	103	.6475	− .0243	− .0278
88	Carillon Stn.	74 22.4	45 34.6	119	.6456	− .0247	− .0288
89	Monalea Stn.	74 24.7	45 34.9	123	.6471	− .0232	− .0274
90		74 18.0	45 35.3	170	.6463	− .0202	− .0260

C=0.1117 mgals/div. PRINCIPAL FACTS FOR GRAVITY STATIONS, 1952 **Worden 44**

Station No.	Station Name	Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
91	Petit Brûlé	74° 1′.9	45° 35′.6	127 ft.	980.6492	−0.0219	−0.0262
92	Côte St. Vincent	74 8.0	45 35.8	186	.6443	− .0215	− .0278
93	Geneva	74 20.8	45 35.9	143	.6748	− .0256	− .0305
94	Watson Stn.	74 28.9	45 36.1	191	.6441	− .0216	− .0281
95	Brown's Gore	74 15.2	45 36.1	161	.6475	− .0211	− .0256
96	St. Hermas	74 10.0	45 36.2	159	.6484	− .0205	− .0260
97	Belle Rivière	74 6.0	45 37.0	127	.6485	− .0247	− .0290
98	Côte St. Hermas	74 10.0	45 37.2	157	.6488	− .0218	− .0272
99		74 24.1	45 37.2	215	.6403	− .0249	− .0322
100	St. Augustine Stn.	74 00.3	45 37.5	183	.6493	− .0193	− .0255
101		74 21.0	45 37.5	207	980.6407	−0.0256	−0.0327
102		74 14.7	45 37.8	240	.6460	− .0177	− .0259
103		74 18.1	45 37.9	254	.6459	− .0166	− .0253
104		74 28.1	45 38.0	295	.6323	− .0263	− .0364
105	Staynerville	74 25.5	45 38.4	260	.6365	− .0262	− .0351
106	Ste. Scholastique	74 5.6	45 38.8	236	.6409	− .0247	− .0327
107	Ste. Hermas Stn.	74 11.7	45 38.9	253	.6457	− .0184	− .0270
108	Deux Montagnes	74 01.1	45 39.8	258	.6504	− .0146	− .0234
109	Upper Lachute	74 14.6	45 40.0	221	.6468	− .0220	− .0295
110	Brownsburg	74 24.2	45 40.6	362	.6352	− .0206	− .0329
111	Hill Head	74 16.2	45 41.2	465	980.6402	−0.0075	−0.0233
112	Canuta	74 8.9	45 41.6	220	.6511	− .0202	− .0277
113	Dalesville	74 24.2	45 42.5	581	.6298	− .0089	− .0286
114	St. Canut	74 4.8	45 43.2	235	.6569	− .0154	− .0234
115		74 17.0	45 43.5	626	.6348	− .0011	− .0224
116	Pine Hill	74 29.2	45 44.3	777	.6243	+ .0014	− .0251
117	St. Colomban	74 8.3	45 44.4	542	.6443	− .0009	− .0194
118		74 00.0	45 44.8	228	.6575	− .0179	− .0256
119		74 35.2	45 38.5	213	.6513	− .0160	− .0232
120		74 43.3	45 38.6	199	.6690	+ .0002	− .0066
121		74 42.0	45 38.6	191	980.6692	−0.0003	−0.0068
122		74 40.6	45 38.7	195	.6656	− .0037	− .0103
123		74 46.9	45 39.0	173	.6646	− .0072	− .0131

C=0.2315 mgals/div. PRINCIPAL FACTS FOR GRAVITY BASES, 1952 **North American 85**

Station Name	Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
Along Highway No. 2.						
Windsor Airport	82° 58′.1	42° 16′.2	623 ft.	980.3264	+0.0016	−0.0196
Windsor	83 02.4	42 19.1	588	.3347	+ .0023	− .0177
Tilbury	82 25.9	42 15.6	587	.3205	− .0068	− .0268
Chatham	82 10.9	42 24.4	594	.3320	− .0078	− .0281
Glencoe (Hy. 80)	81 42.7	42 44.9	728	.3492	− .0087	− .0335
London	81 15.1	42 59.0	814	.3585	− .0124	− .0402
Woodstock	80 45.5	43 07.8	990	.3574	− .0102	− .0439
Paris	80 23.2	43 11.9	829	.3708	− .0181	− .0464

C=0.2315 mgals/div. PRINCIPAL FACTS FOR GRAVITY BASES, 1952 North American 85

Station Name	Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies Free Air	Bouguer
Along Highway No. 2.—Concl.								
Hamilton	79°	52′2	43°	15′5	316 ft.	980.4092	− .0334	− .0441
Toronto	79	23.5	43	40.0	370	.4444	− .0299	− .0425
Whitby	78	56.6	43	52.7	310	.4676	− .0314	− .0420
Bowmanville	78	41.4	43	54.9	365	.4722	− .0250	− .0374
Port Hope	78	17.2	43	57.0	298	.4721	− .0345	− .0446
Colborne	77	58.6	44	00.8	361	.4838	− .0225	− .0348
Trenton	77	34.8	44	06.5	256	.5041	− .0206	− .0294
Belleville	77	22.8	44	09.6	260	.5095	− .0197	− .0286
Napanee	76	57.3	44	15.2	315	.5169	− .0155	− .0262
Kingston	76	28.9	44	13.7	254	.5249	− .0109	− .0196
Brockville	75	41.3	44	35.4	310	.5457	− .0175	− .0281
Prescott	75	31.5	44	42.8	311	.5665	− .0077	− .0183
Morrisburg	75	11.3	44	53.9	270	.6070	+ .0122	+ .0030
Cornwall	74	44.0	45	01.9	193	.6181	+ .0040	− .0026
Lancaster	74	30.2	45	08.4	164	.6350	+ .0084	+ .0028
Along Highway No. 3								
Simcoe	80	18.7	42	50.3	714	980.3461	−0.0212	−0.0456
Cayuga	79	51.8	42	56.9	600	.3675	− .0205	− .0409
Port Colborne	79	15.1	42	53.3	583	.3677	− .0165	− .0363
Along Highway No. 4.								
Centralia Airport	81	30.2	43	17.5	813	980.3920	−0.0068	−0.0345
Along Highway No. 6.								
Mt. Forest	80	44.8	43	58.6	1353	980.4127	+0.0030	−0.0431
Owen Sound	80	56.7	44	34.0	600	.5165	− .0174	.0378
Along Highway No. 7.								
Guelph	80	14.7	43	32.8	1042	980.3801	−0.0202	−0.0557
Brampton	79	45.9	43	41.2	715	.4182	− .0254	.0498
Malton Airport	79	38.1	43	41.6	565	.4306	− .0278	− .0470
Sunderland	79	03.7	44	16.0	859	.4694	− .0130	− .0423
Lindsay	78	44.5	44	21.2	847	.4791	− .0122	− .0411
Peterborough	78	19.3	44	18.5	673	.4883	−0.0154	−0.0383
Havelock	77	52.9	44	26.0	700	.4939	− .0185	− .0423
Madoc	77	29.1	44	30.4	575	.5211	− .0097	− .0293
Actinolite	77	19.2	44	33.2	555	.5328	− .0041	− .0230
Kaladar	77	07.0	44	38.7	705	.5225	− .0085	− .0325
Sharbot Lake	76	41.3	44	46.4	650	.5436	− .0042	− .0263
Perth	76	15.0	44	53.9	439	.5595	− .0194	− .0344
Along Highway No. 8								
Niagara Falls	79	04.8	43	05.6	606	980.3862	−0.0142	−0.0348
St. Catharines	79	14.5	43	09.7	369	.4127	− .0162	− .0288
Along Highway No. 10.								
Orangeville	80	05.4	43	54.8	1397	980.3919	−0.0080	−0.0556

C=0.2315 mgals/div. PRINCIPAL FACTS FOR GRAVITY BASES, 1952 North American 85

Station Name	Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies Free Air	Bouguer
Along Highway No. 11.								
Barrie	79°	41'.3	44°	23'.3	727 ft.	980.4854	−0.0204	−0.0452
Hawkestone	79	28.5	44	30.0	780	.4947	− .0162	− .0428
Orillia	79	24.7	44	36.5	723	.5143	− .0117	− .0363
Atherlea (Hy. 12)	79	21.8	44	36.2	738	.5118	− .0124	− .0375
Gravenhurst	79	22.3	44	55.2	832	.5394	− .0045	− .0329
Utterson	79	19.7	45	12.7	1036	.5564	+ .0053	− .0299
Huntsville	79	12.9	45	19.3	959	.5697	+ .0015	− .0312
Sundridge	79	23.9	45	46.0	1100	.5876	− .0075	− .0450
Trout Creek	79	21.5	45	59.2	1027	.6012	− .0207	− .0557
Callandar	79	22.0	46	13.3	670	.6440	− .0327	− .0555
North Bay	79	28.0	46	18.9	677	.6550	− .0294	− .0525
Along Highway No. 15.								
Merrickville	75	50.5	44	55.3	357	980.5793	−0.0094	−0.0216
Smith's Falls	76	01.0	44	54.2	428	.5767	− .0037	− .0183
Carleton Place	76	08.4	45	08.2	453	.5814	− .0177	− .0331
Richmond	75	49.5	45	11.0	310	.6076	− .0091	− .0197
Along Highway No. 16.								
Kemptville	75	38.6	45	00.8	319	980.5819	−0.0187	−0.0296
North Gower	75	43.1	45	07.9	300	.6110	− .0021	− .0123
Manotick	75	41.1	45	13.6	275	.6204	− .0036	− .0130
Along Highway No. 17.								
Hawkesbury	74	36.3	45	36.6	147	980.6551	−0.0156	−0.0206
Plantaganet	74	59.0	45	31.0	168	.6375	− .0227	− .0284
Rockcliffe Airport	75	38.3	45	27.4	178	.6388	− .0151	− .0211
Ottawa	75	42.9	45	23.6	274.3	.6220	− .0171	− .0264
Arnprior	76	21.4	45	25.9	299	.6193	−0.0210	−0.0312
Renfrew	76	41.5	45	28.1	422	.6271	− .0049	− .0193
Cobden	76	53.1	45	37.6	476	.6257	− .0155	− .0317
Pembroke	77	07.3	45	49.4	410	.6336	− .0315	− .0455
Chalk River	77	27.1	46	01.1	522	.6410	− .0321	− .0499
Stonecliff	77	53.7	46	12.8	562	.6561	− .0299	− .0491
Mattawa	78	42.3	46	18.7	563	.6489	− .0459	− .0651
Rutherglen	79	02.3	46	16.2	789	.6282	− .0416	− .0685
Sturgeon Falls	79	55.7	46	22.0	688	.6742	− .0138	− .0372
Hagar	80	25.0	46	29.8	691	.7026	+ .0069	− .0166
Sudbury	81	00.0	46	29.8	881	.6860	+ .0044	− .0256
Worthington	81	27.1	46	22.9	775	.6861	+ .0049	− .0215
Espanola	81	46.0	46	16.1	672	.6742	− .0065	− .0294
Webbwood	81	52.7	46	16.0	661	.6761	− .0054	− .0279
Spanish	82	21.0	46	11.6	610	.6575	− .0222	− .0430
Blind River	82	57.4	46	10.8	602	.6493	− .0300	− .0505
Iron Bridge	83	13.3	46	16.7	619	.6542	− .0324	− .0535
Bruce Station	83	45.7	46	19.0	680	.6652	− .0190	− .0422
Sault Ste. Marie	84	19.6	46	30.5	600	.6841	− .0250	− .0454
Along Highway No. 21.								
Goderich	81	42.7	43	44.6	718	980.4452	−0.0033	−0.0270
Kincardine	81	38.2	44	10.5	649	.4702	− .0237	− .0458

C = 0.2315 mgals/div. PRINCIPAL FACTS FOR GRAVITY BSES, 1952 **North American 85**

Station Name	Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies Free Air	Bouguer
Along Highway No. 22.						
Watford	81° 52′.5	42° 57′.1	796 ft.	980.3686	−0.0012	−0.0283
Along Highway No. 31.						
Winchester	75 20.8	45 04.9	250	980.5984	−0.0149	−0.0234
Vernon	75 27.9	45 09.9	289	.5999	− .0172	− .0271
Along Highway No. 34.						
Alexandria	74 38.3	45 19.0	257	980.6369	+0.0031	−0.0057
Along Highway No. 40.						
Wallaceburg	82 22.5	42 35.2	584	980.3529	−0.0040	−0.0239
Sarnia	82 24.4	42 58.1	599	.4103	− .0041	− .0245
Along Highway No. 60.						
Algonquin Park	78 35.7	45 33.1	1419	980.5526	+0.0069	−0.0415
Whitney	78 14.0	45 29.8	1266	.5533	− .0018	− .0449
Barry's Bay	77 40.5	45 29.5	984	.5652	− .0160	− .0496
Eganville	77 06.1	45 32.4	551	.6089	− .0174	− .0361
Along Highway No. 62						
Steenburg	77 39.2	44 50.5	Elevation Unknown	980.5158		
Bancroft	77 51.6	45 03.5	1085	.5302	−0.0024	−0.0394
BASES IN QUEBEC						
Along Highway No. 2.						
Ste. Anne de Bellevue	73 56.6	45 24.5	110	980.6463	−0.0097	−0.0134
Dorval Airport	73 45.5	45 27.3	97	.6454	− .0160	− .0193
Montreal	73 34.0	45 30.0	151	.6499	− .0104	− .0155
Pointe aux Trembles	73 29.5	45 38.4	42	.6581	− .0251	− .0266
St. Sulpice	73 21.2	45 49.6	35	.6786	− .0221	− .0233
Berthierville	73 10.7	46 05.0	29	.6880	− .0365	− .0375
Along Highway No. 41.						
Lachute	74 20.0	45 39.4	226	980.6470	−0.0204	−0.0281
St. Jerome	74 00.2	45 46.8	310	.6609	− .0097	− .0203
St. Jacques	73 34.3	45 56.9	196	.6797	− .0169	− .0235
Jolliette	73 26.2	46 01.3	186	.6906	− .0135	− .0198

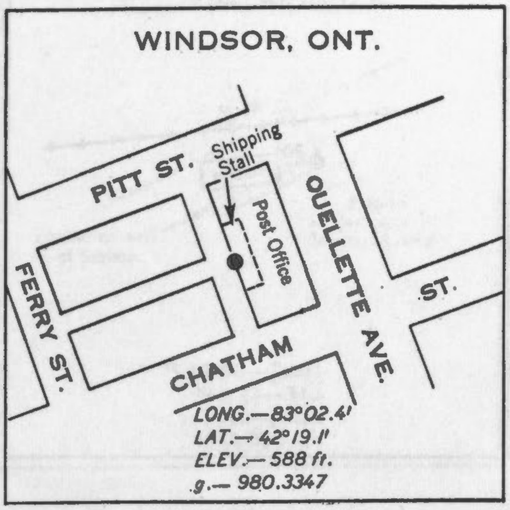
APPENDIX B

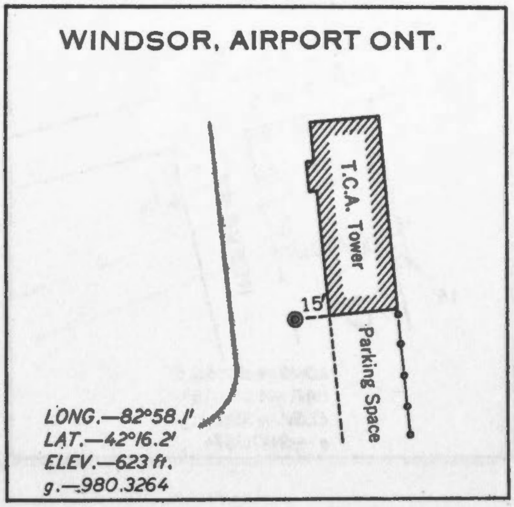
Description of Sites of Primary Gravity Bases

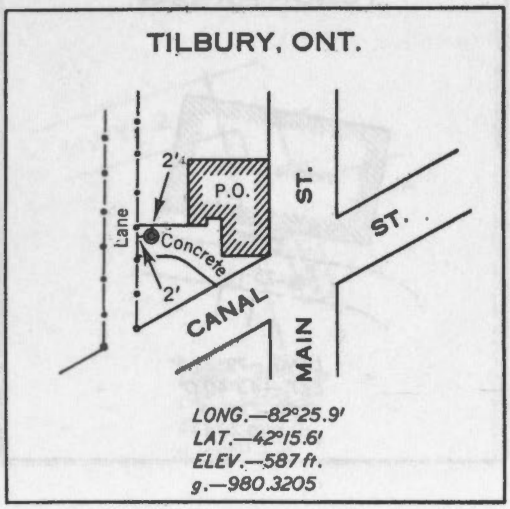
APPENDIX B

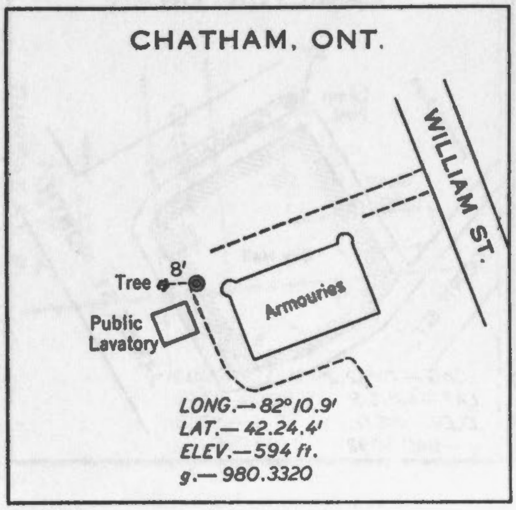
Description of Sites of Primary Gravity Bases

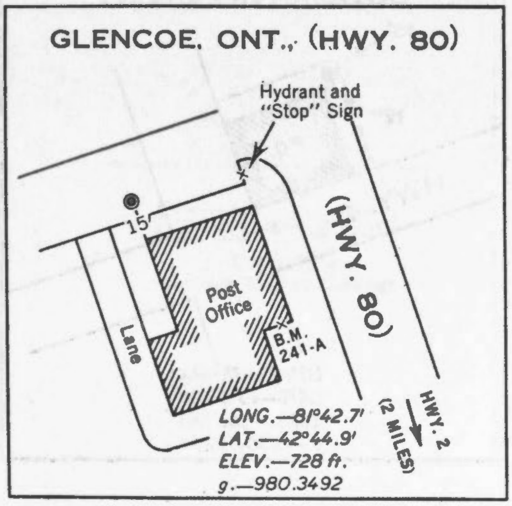
ONTARIO
HIGHWAY No. 2

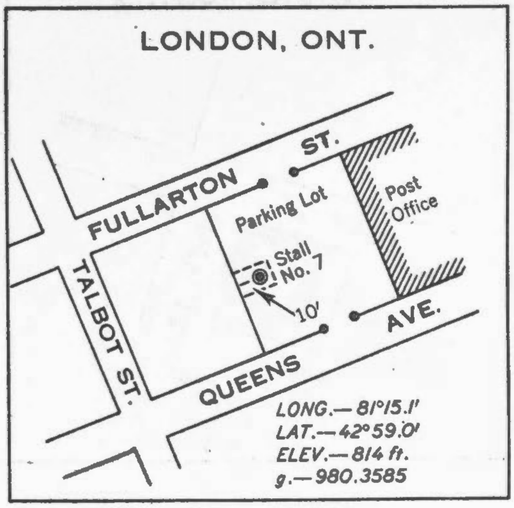






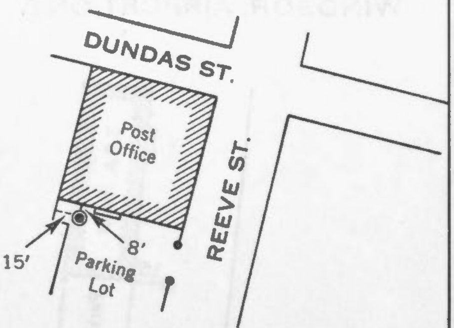






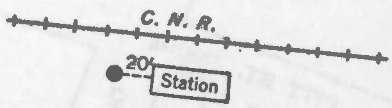
HIGHWAY No. 2 (CONT'D)

WOODSTOCK, ONT.



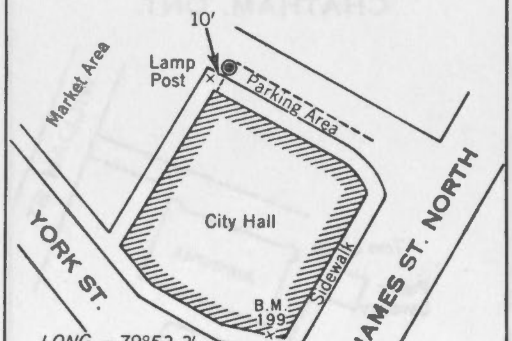
LONG.—80°45.5'
LAT.—43°07.8'
ELEV.—990 ft.
g.—980.3574

PARIS, ONT.



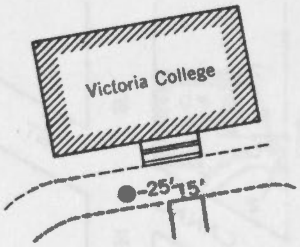
LONG.—80°23.2'
LAT.—43°11.9'
ELEV.—829 ft.
g.—980.3708

HAMILTON, ONT.



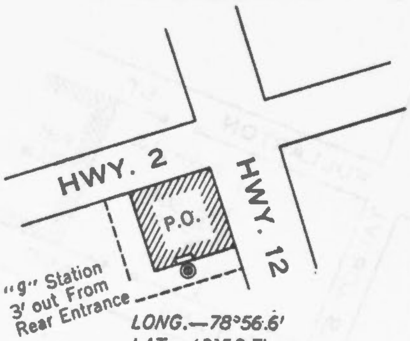
LONG.—79°52.2'
LAT.—43°15.5'
ELEV.—316 ft.
g.—980.4092

TORONTO, ONT.



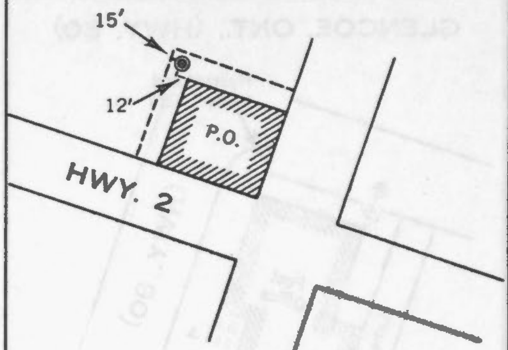
LONG.—79°23.5'
LAT.—43°40.0'
ELEV.—370 ft.
g.—980.4444

WHITBY, ONT.



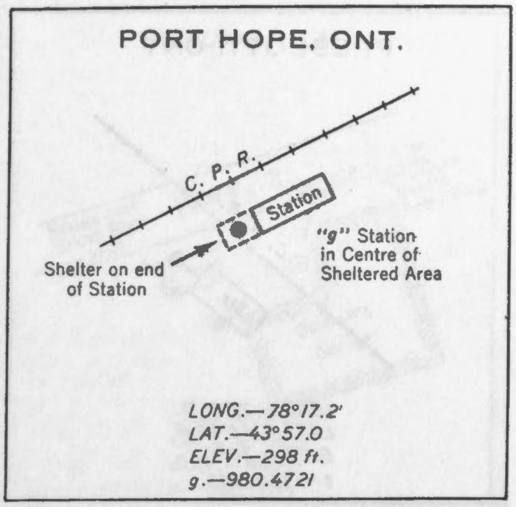
LONG.—78°56.6'
LAT.—43°52.7'
ELEV.—310 ft.
g.—980.4676

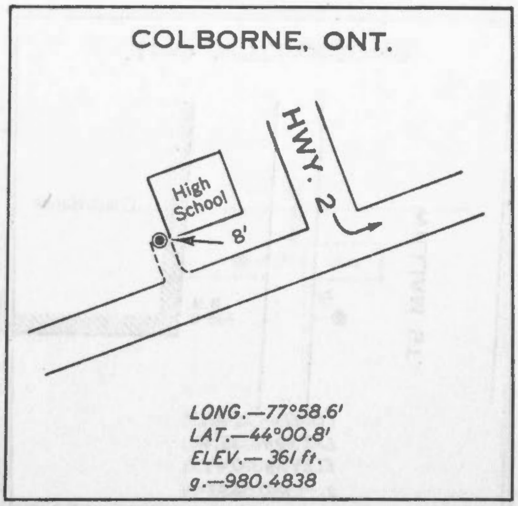
BOWMANVILLE, ONT.

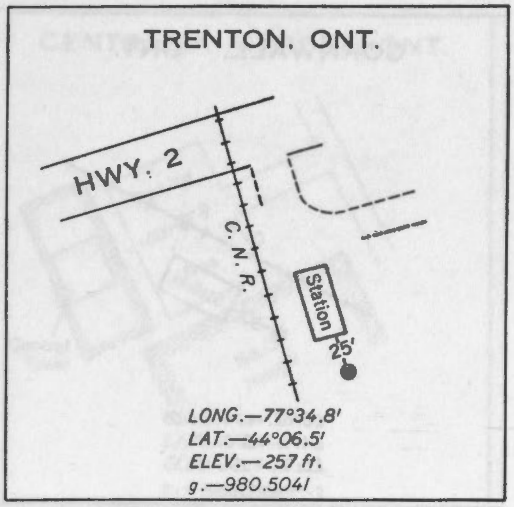


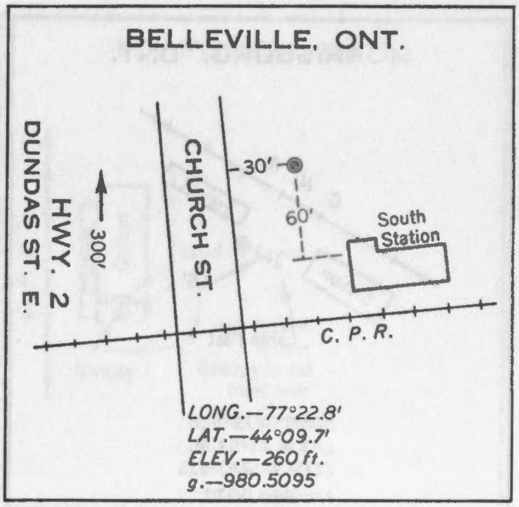
LONG.—78°41.4'
LAT.—43°54.9'
ELEV.—365 ft.
g.—980.4722

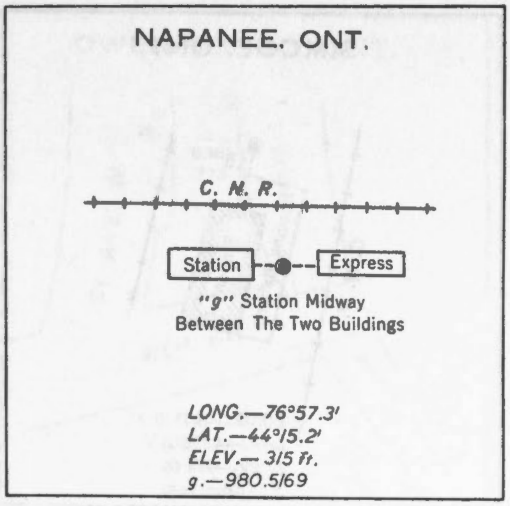
HIGHWAY No. 2 (CONT'D)





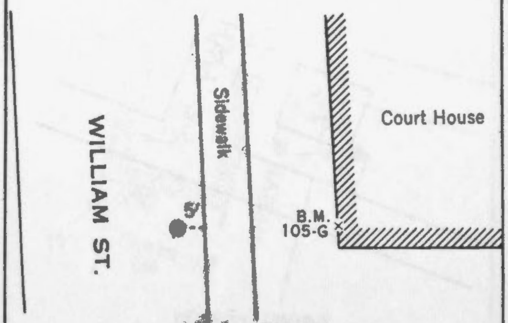






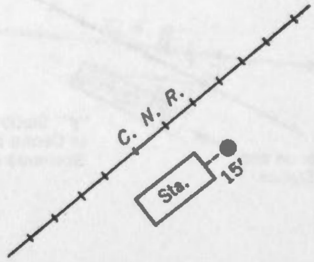
HIGHWAY No. 2 (CONT'D)

BROCKVILLE, ONT.



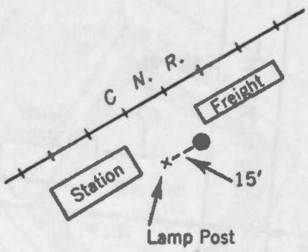
LONG.—75°41.3'
LAT.—44°35.4'
ELEV.—310 ft.
g.—980.5457

PRESCOTT, ONT



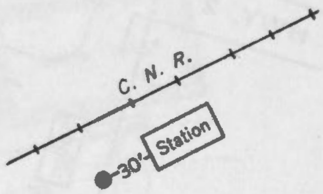
LONG.— 75°31.5'
LAT.— 44°42.8'
ELEV.— 311 ft.
g.— 980.5665

MORRISBURG, ONT.



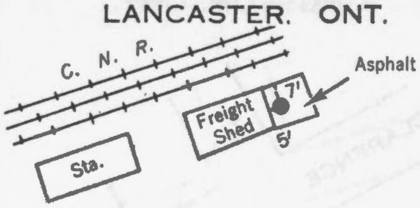
LONG.— 75°11.3'
LAT.— 44°53.9'
ELEV.— 270 ft.
g.— 980.6070

CORNWALL, ONT.



LONG.—74°44.0'
LAT.—45°01.9'
ELEV.— 193 ft.
g.—980.6181

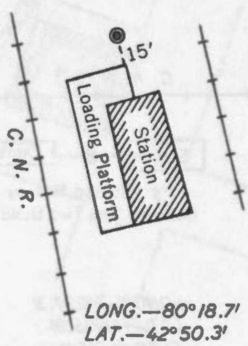
LANCASTER, ONT.



LONG.—74°30.2'
LAT.—45°08.4'
ELEV.—164 ft.
g.—980.6350

HIGHWAY No. 3

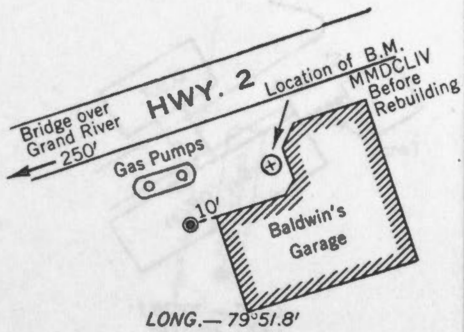
SIMCOE, ONT.



LONG.—80°18.7'
LAT.—42°50.3'
ELEV.—714 ft.
g.—980.3461

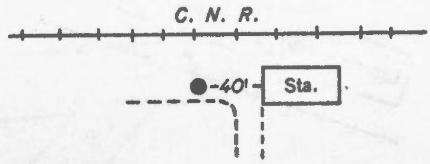
HIGHWAY No. 3 (CONT'D)

CAYUGA. ONT.



LONG.—79°51.8′
LAT.—42°56.9′
ELEV.—600 ft.
g.—980.3675

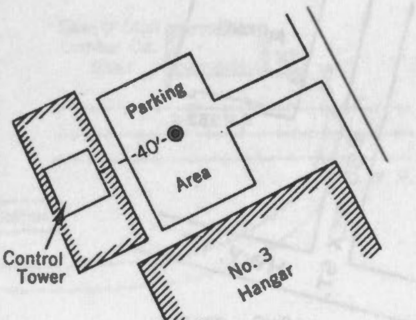
PORT COLBORNE ONT.



LONG.—79°15.1′
LAT.—42°53.3′
ELEV.—583 ft.
g.—980.3677

HIGHWAY No. 4

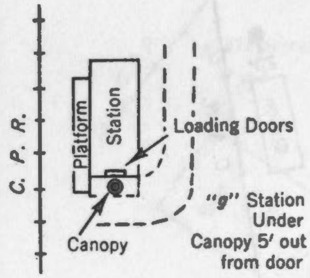
CENTRALIA AIRPORT, ONT.



LONG.—81°30.2′
LAT.—43°17.5′
ELEV.—813 ft.
g.—980.3920

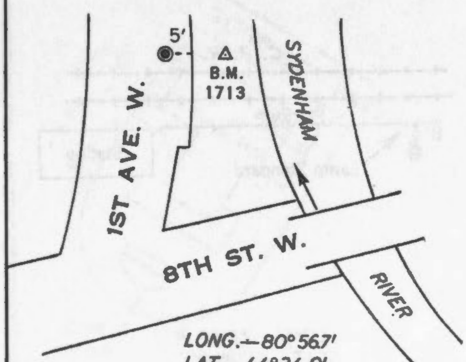
HIGHWAY No. 6

MT. FOREST, ONT.



LONG.—80°44.8′
LAT.—43°58.6′
ELEV.—1353 ft.
g.—980.4127

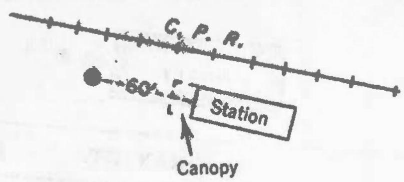
OWEN SOUND, ONT.



LONG.—80°56.7′
LAT.—44°34.0′
ELEV.—600 ft.
g.—980.5165

HIGHWAY No. 7

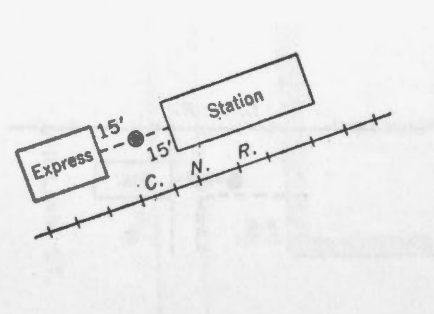
GUELPH, ONT.



LONG.—80°14.7′
LAT.—43°32.8′
ELEV.—1042 ft.
g.—980.3801

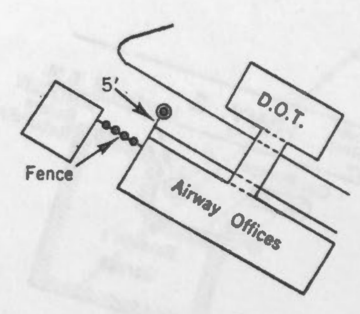
HIGHWAY No. 7 (CONT'D)

BRAMPTON, ONT.



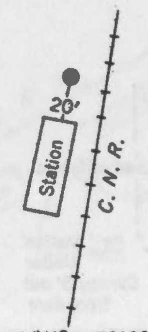
LONG.—79°45.9'
LAT.—43°41.2'
ELEV.—715 ft.
g.—980.4182

MALTON AIRPORT, ONT.



LONG.—79°38.1'
LAT.—43°41.6'
ELEV.—565 ft.
g.—980.4306

SUNDERLAND, ONT.

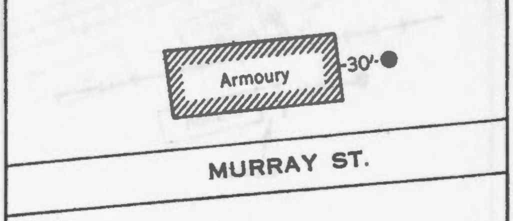


LONG.—79°03.7'
LAT.—44°16.0'
ELEV.—859 ft.
g.—980.4694

LINDSAY, ONT.

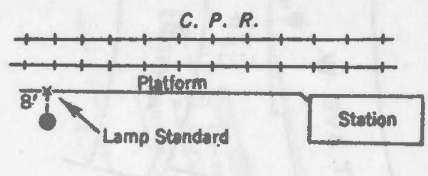
LONG.—78°44.5'
LAT.—44°21.2'
ELEV.—847 ft.
g.—980.4791

PETERBOROUGH, ONT.



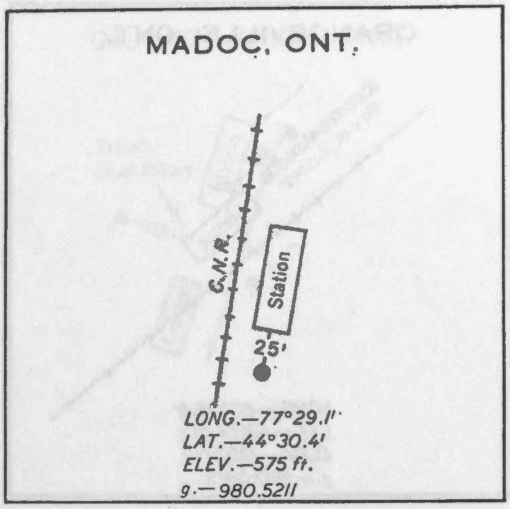
LONG.—78°19.3'
LAT.—44°18.5'
ELEV.—673 ft.
g.—980.4883

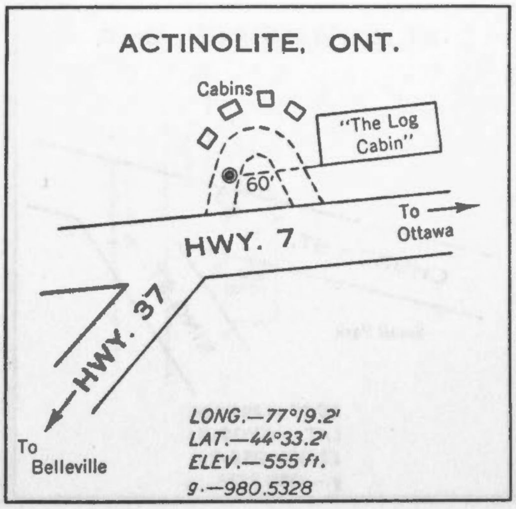
HAVELOCK, ONT.

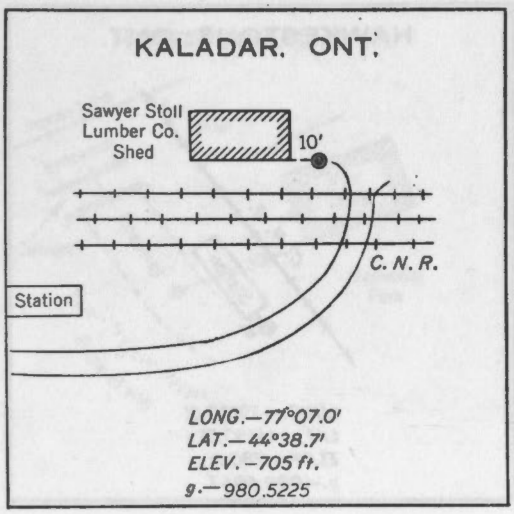


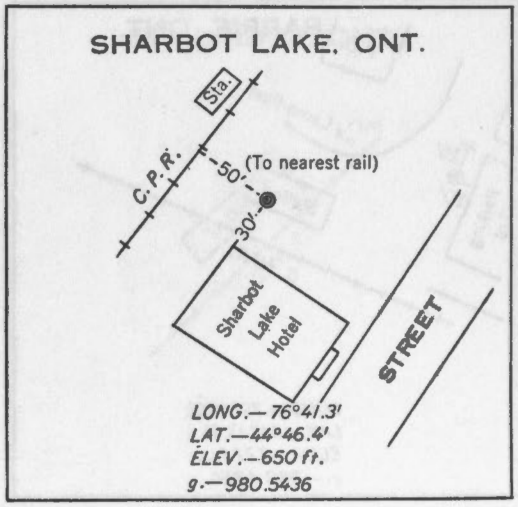
LONG.—77°52.9'
LAT.—44°26.0'
ELEV.—700 ft.
g.—980.4939

HIGHWAY No. 7 (CONT'D)

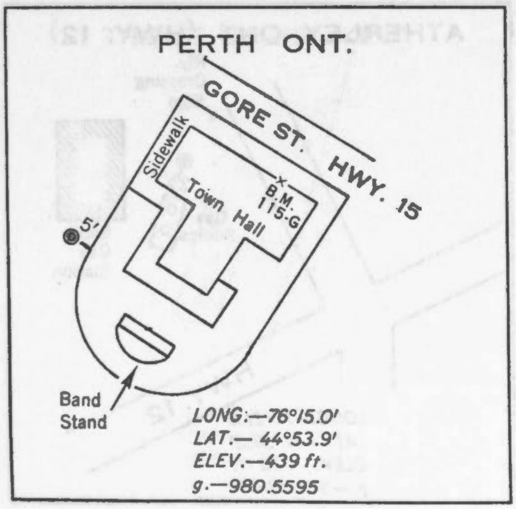


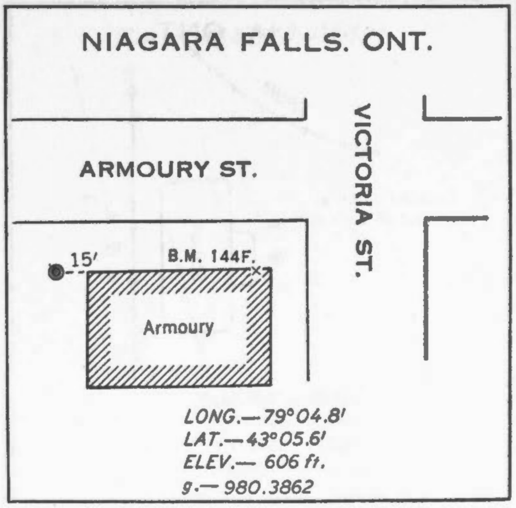




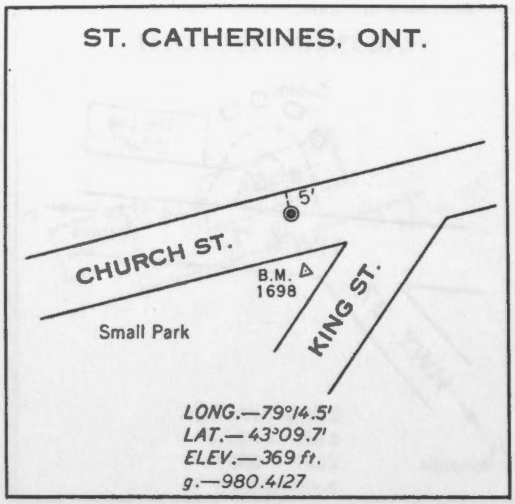


HIGHWAY No. 8

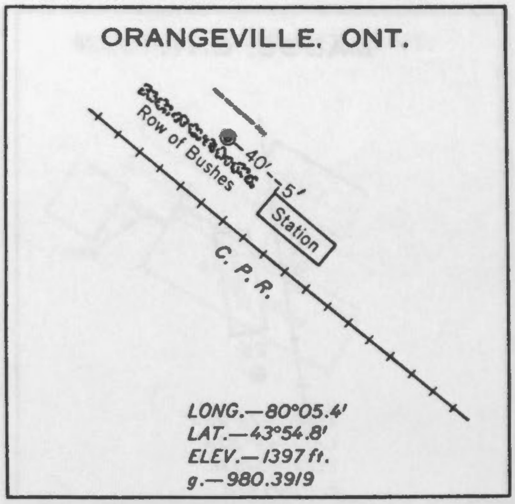




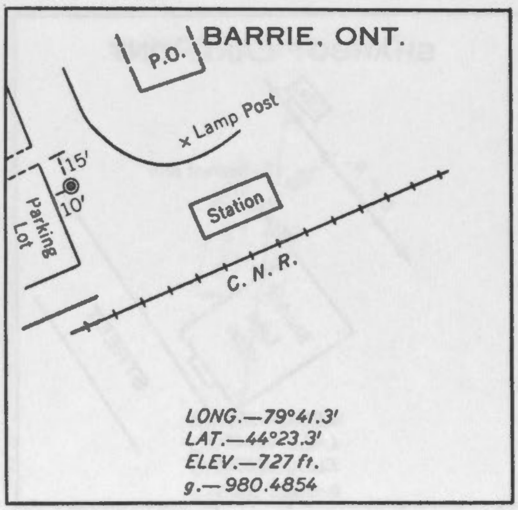
HIGHWAY No. 8 (CONT'D)

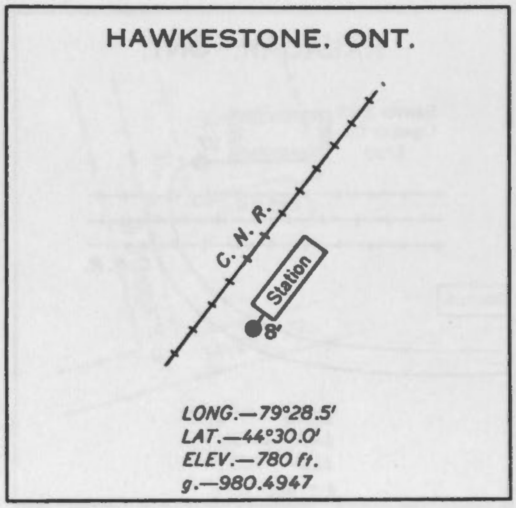


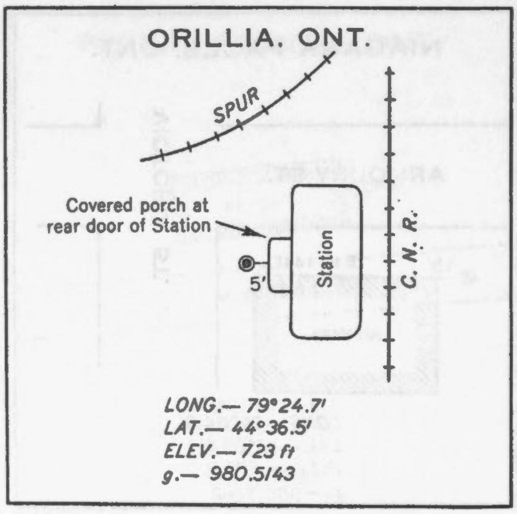
HIGHWAY No. 10

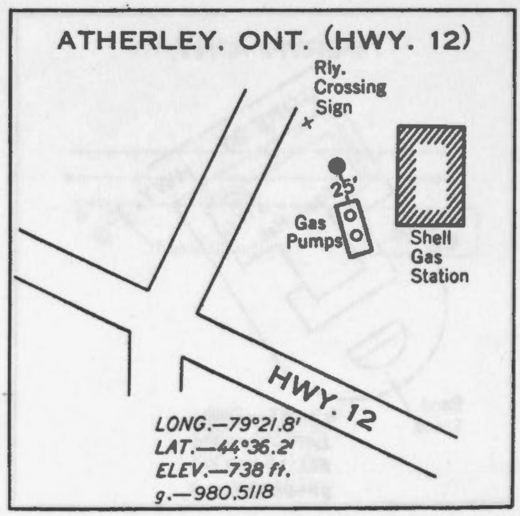


HIGHWAY No.11

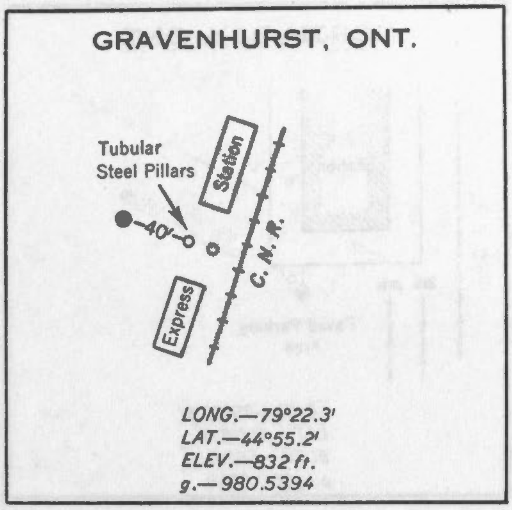


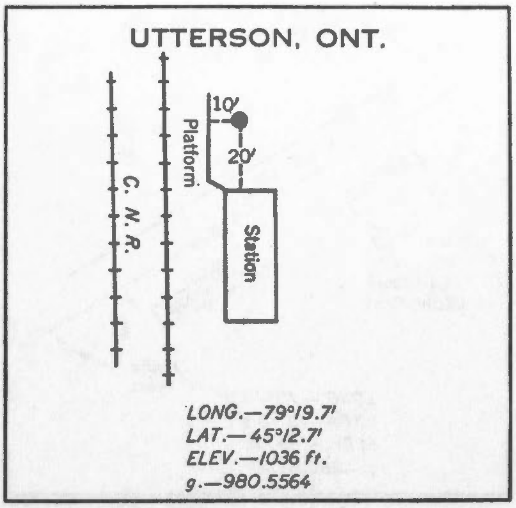


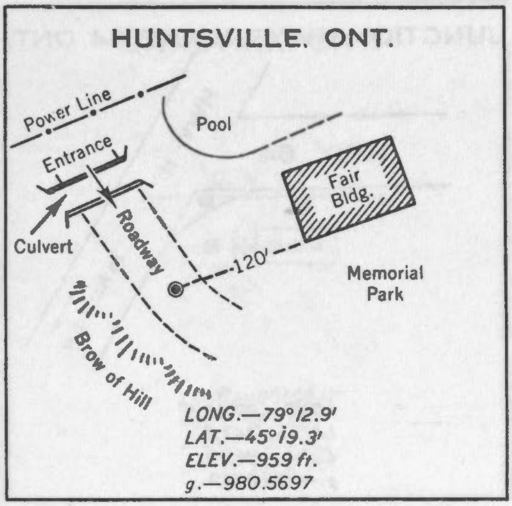


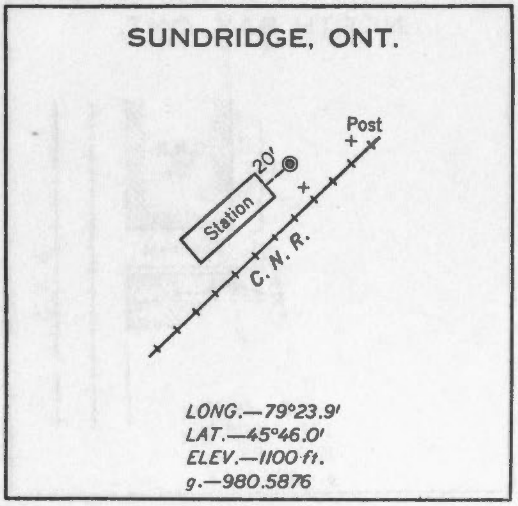


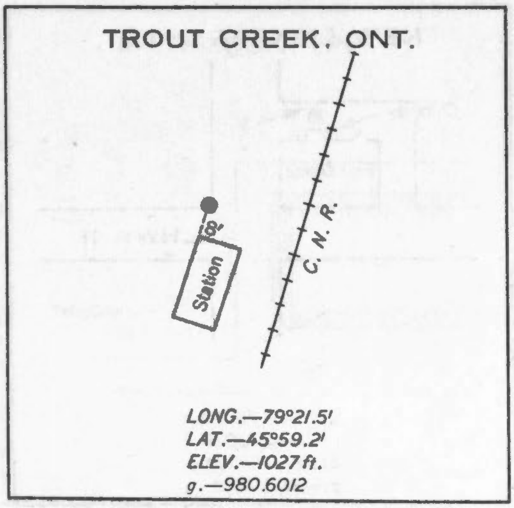
HIGHWAY No. 11 (CONT'D)

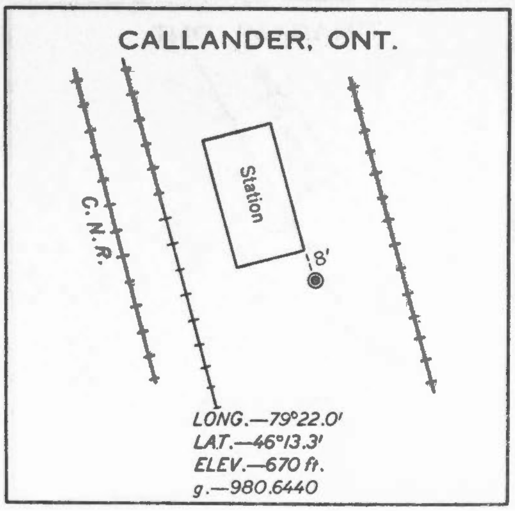






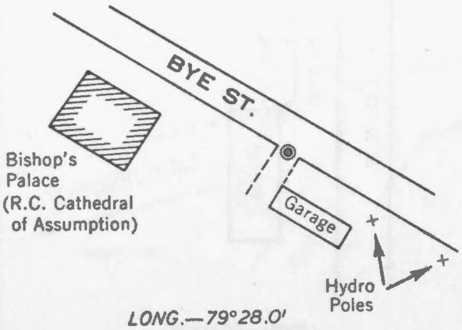






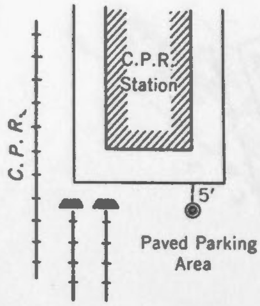
HIGHWAY No. 11 (CONT'D)

NORTH BAY, ONT.



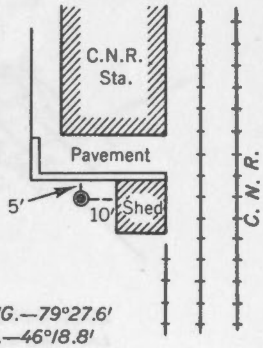
LONG.—79°28.0'
LAT.— 46°18.9'
ELEV.— 677 ft.
g.—980.6550

NORTH BAY, ONT.



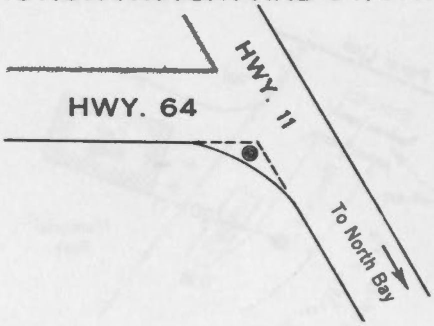
LONG.—79°27.9'
LAT.—46°18.6'
ELEV.—662 ft.
g.—980.6568

NORTH BAY, ONT.



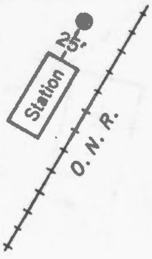
LONG.—79°27.6'
LAT.—46°18.8'
ELEV.—691 ft.
g.—980.6549

JUNCTION HWYS. 11 AND 64. ONT.



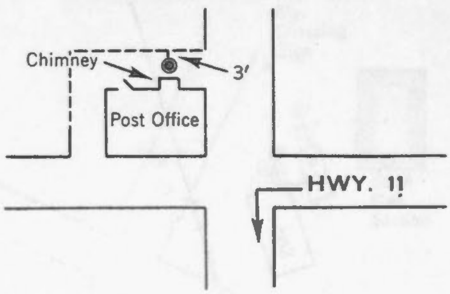
LONG.—79°49.9'
LAT.—46°43.1'
ELEV.— 965 ft.
g.—980.6849

TIMAGAMI, ONT.



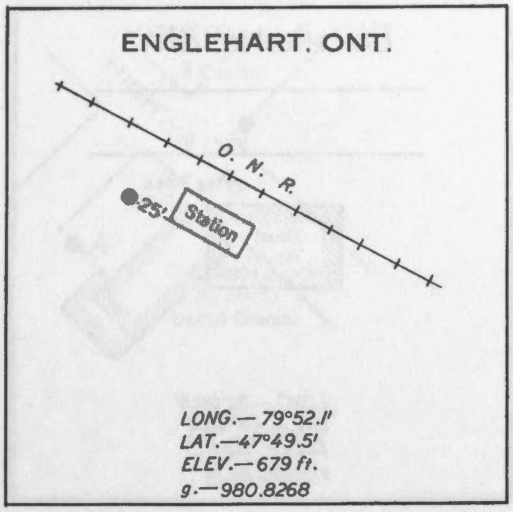
LONG.—79°47.0'
LAT.—47°03.9'
ELEV.— 986 ft.
g.—980.7250

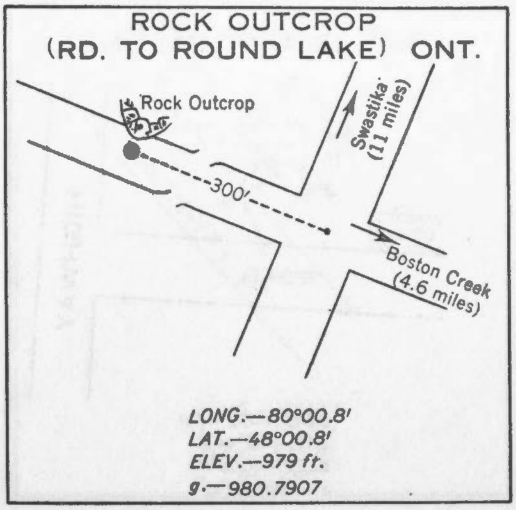
NEW LISKEARD, ONT.

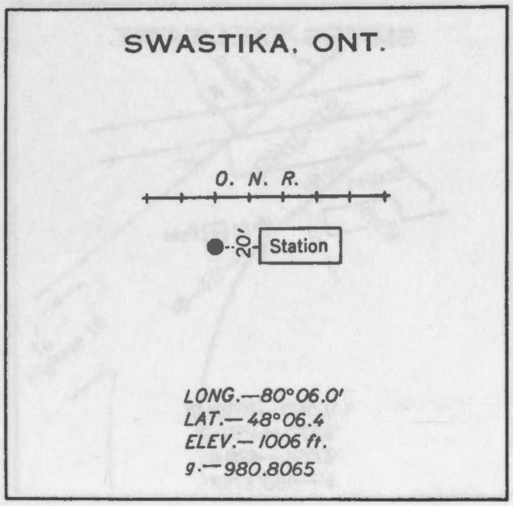


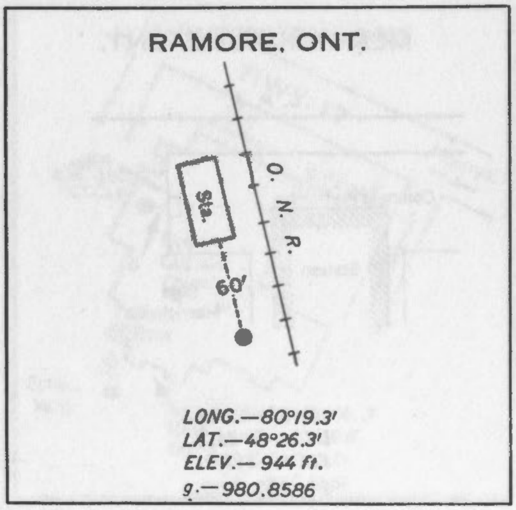
LONG.— 79°40.3'
LAT.—47°30.6'
ELEV.— 620 ft.
g.—980.7863

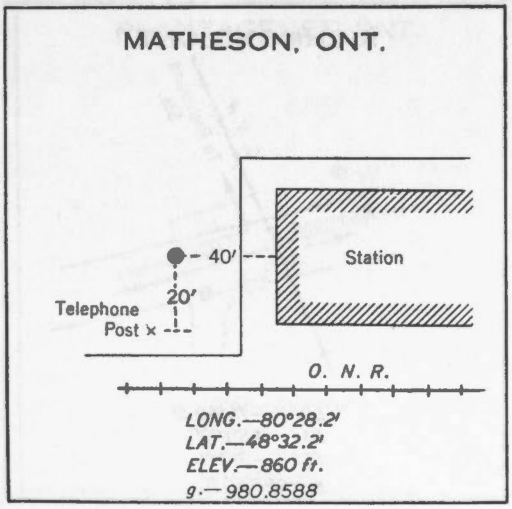
HIGHWAY No. 11 (CONT'D)

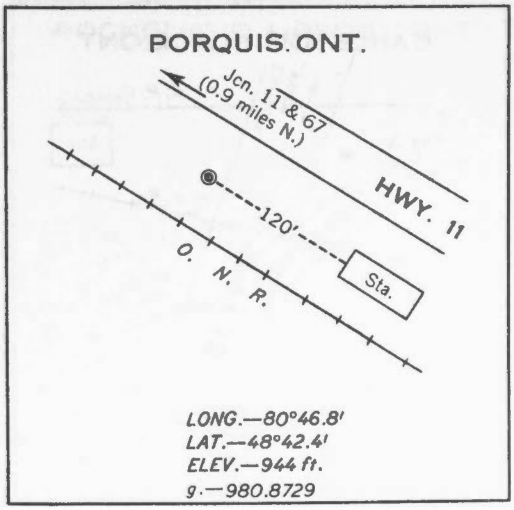






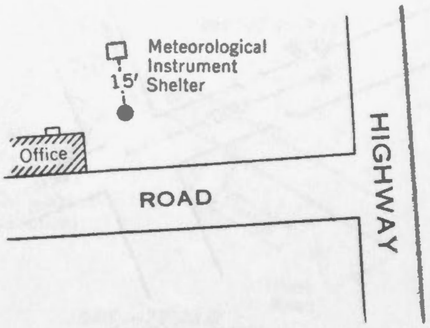






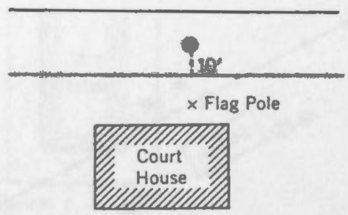
HIGHWAY No. 11 (CONT'D)

PORQUIS AIRPORT, ONT.



LONG.—80°47.1'
LAT.—48°44.4'
ELEV.—1002 ft.
g.—980.8732

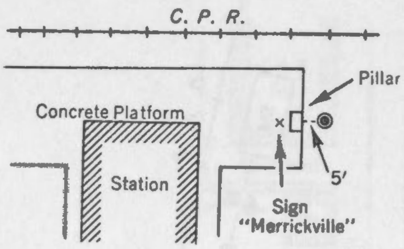
COCHRANE, ONT.



LONG.—81°00.6'
LAT.—49°03.6'
ELEV.—917 ft.
g.—980.8874

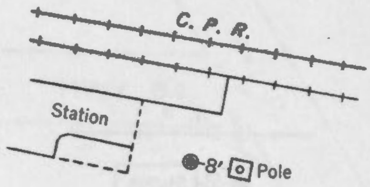
HIGHWAY 15

MERRICKVILLE, ONT.



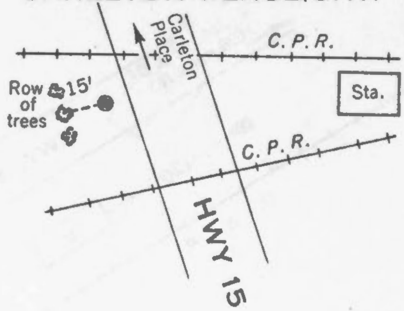
LONG.—75°50.5'
LAT.—44°55.3'
ELEV.—357 ft.
g.—980.5793

SMITHS FALLS, ONT.



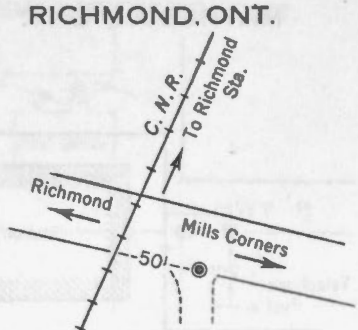
LONG.—76°01.0'
LAT.—44°54.2'
ELEV.—428 ft.
g.—980.5767

CARLETON PLACE, ONT.



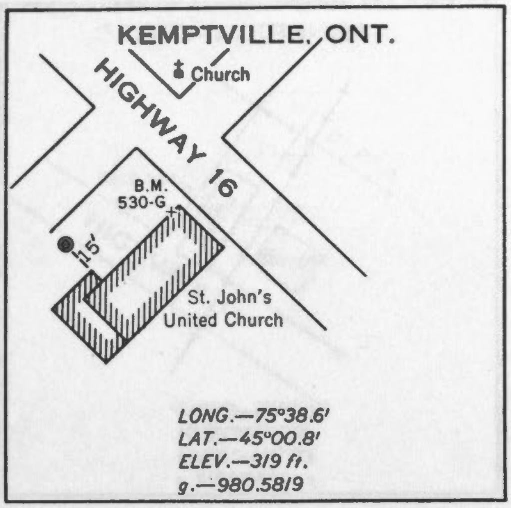
LONG.—76°08.4'
LAT.—45°08.2'
ELEV.—453 ft.
g.—980.5814

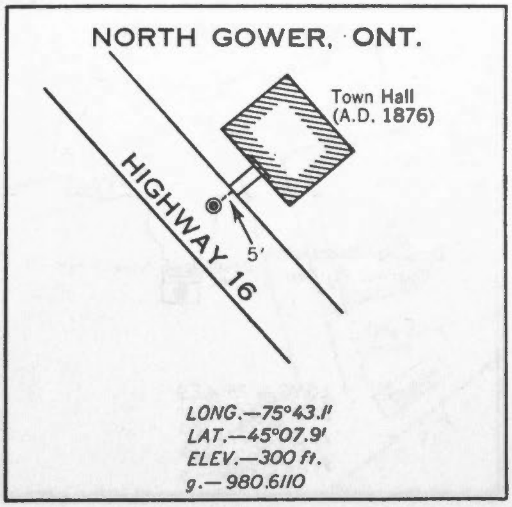
RICHMOND, ONT.



LONG.—75°49.5'
LAT.—45°11.0'
ELEV.—310 ft.
g.—980.6076

HIGHWAY No.16





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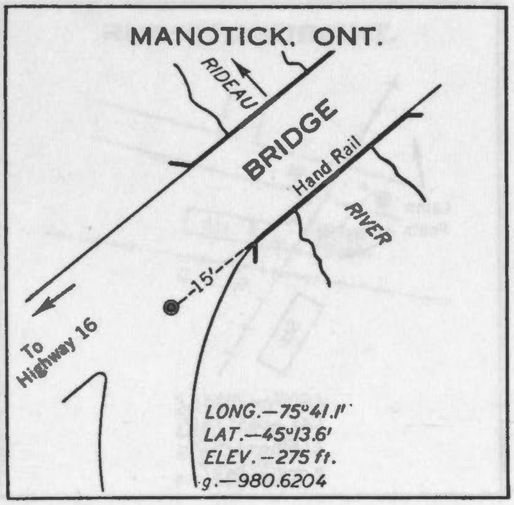

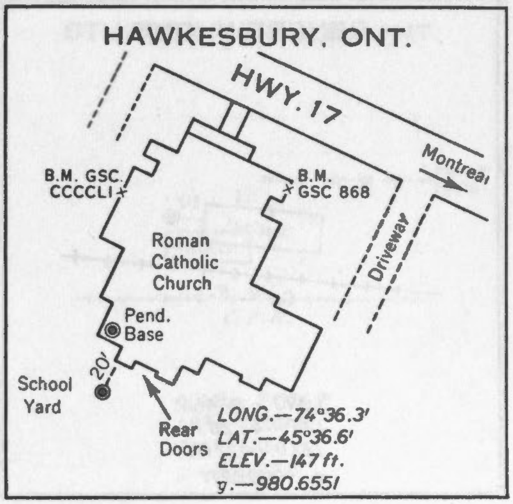

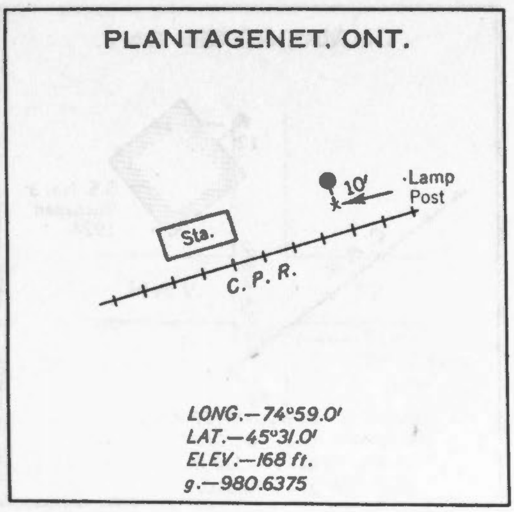

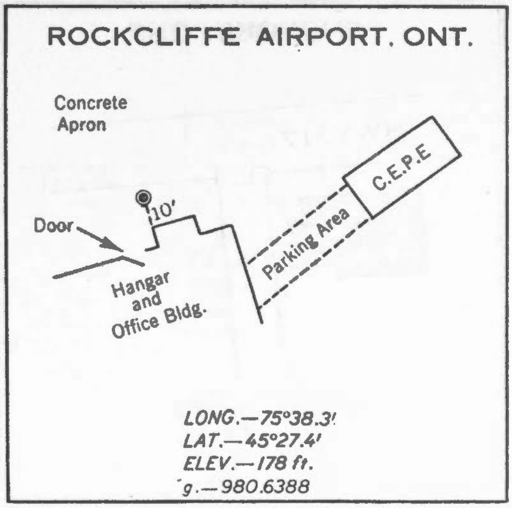

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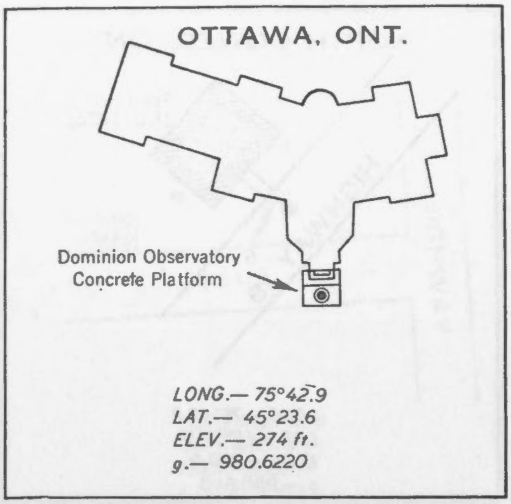

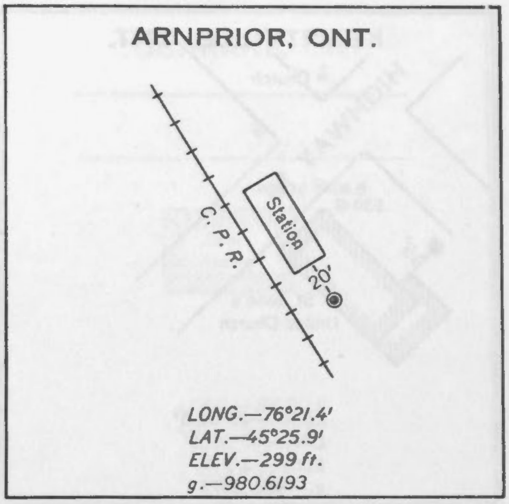

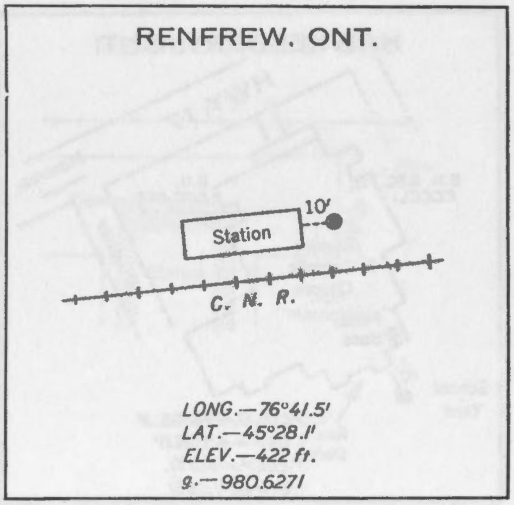

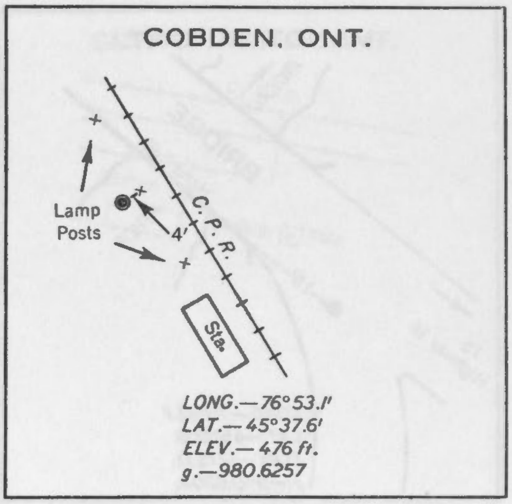

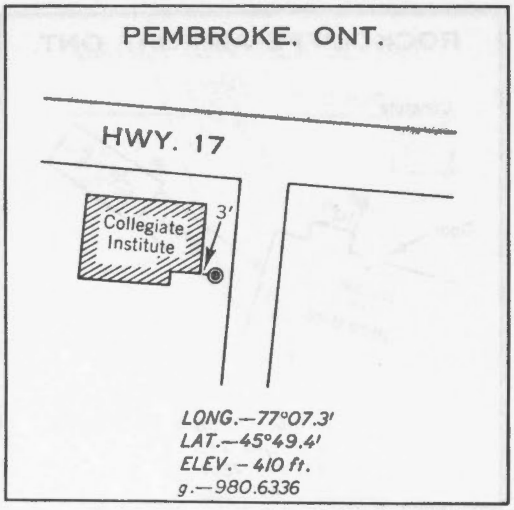

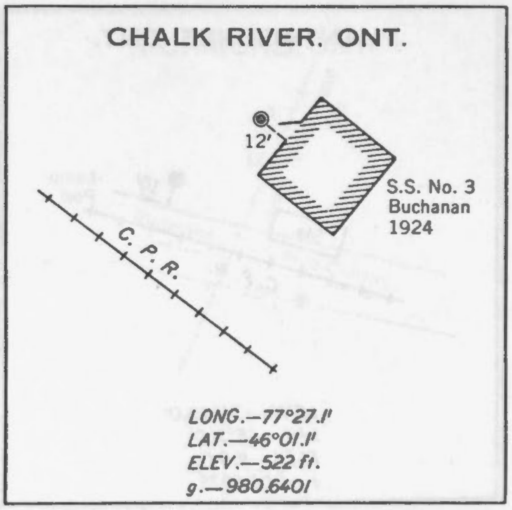

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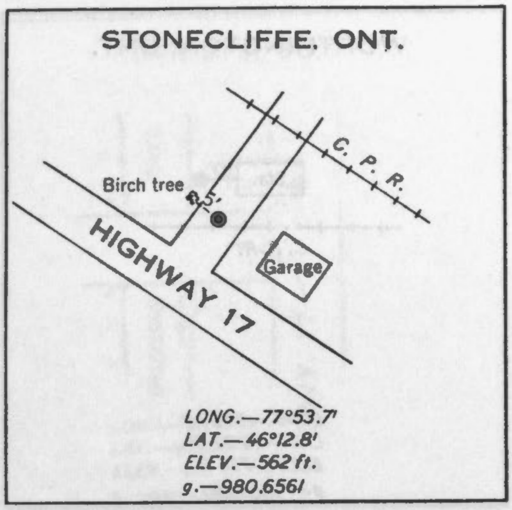
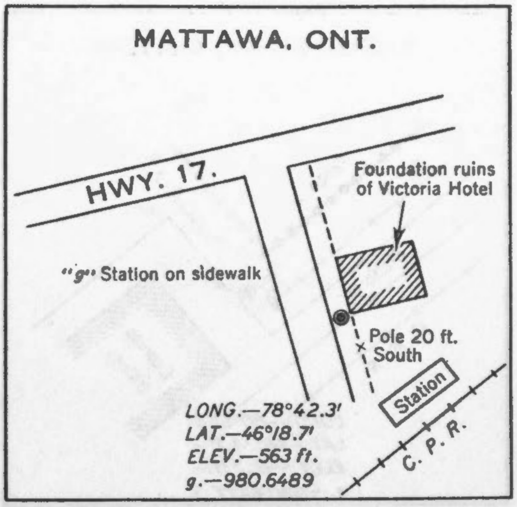
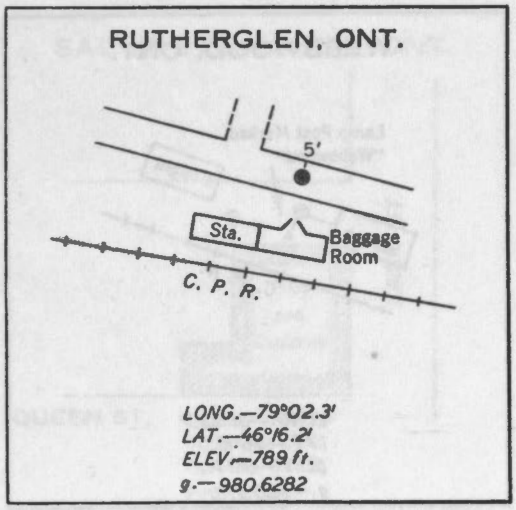
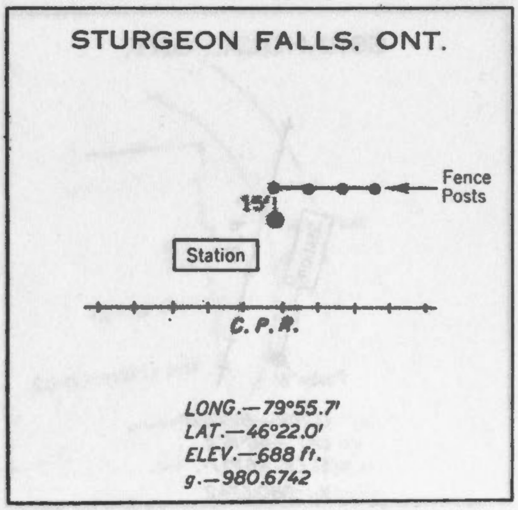
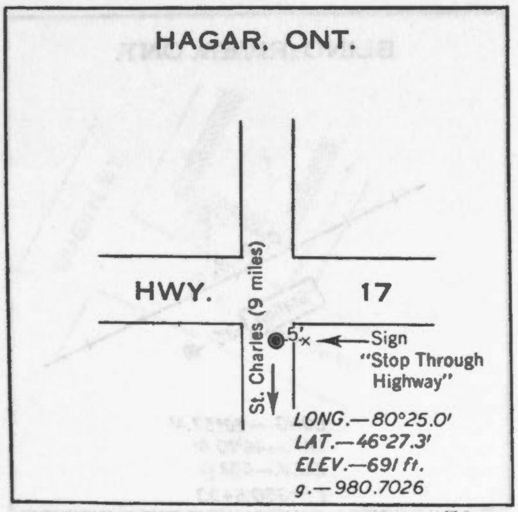
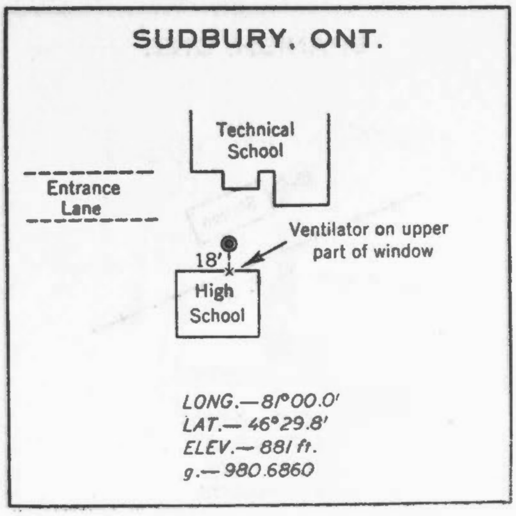






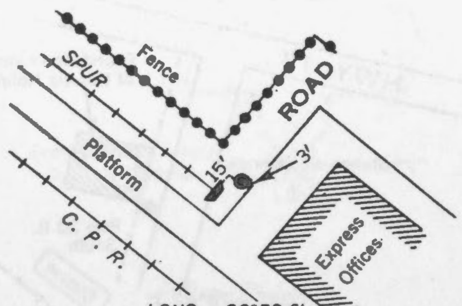






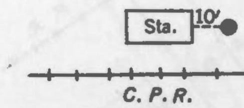
HIGHWAY No. 17 (CONT'D)

SUDBURY, ONT.



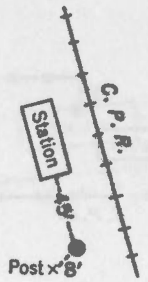
LONG.—80°59.6'
LAT.—46°29.2'
ELEV.—857 ft.
g.—980.6877

WORTHINGTON, ONT.



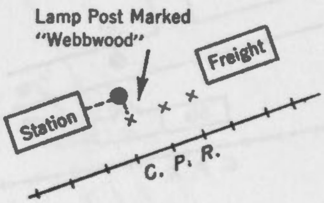
LONG.—81°27.1'
LAT.—46°22.9'
ELEV.—775 ft.
g.—980.6861

ESPANOLA, ONT.



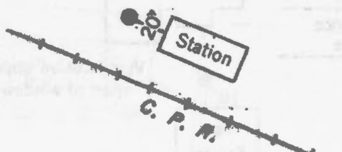
LONG.—81°46.0'
LAT.—46°16.1'
ELEV. -672 ft.
g.—980.6742

WEBBWOOD, ONT.



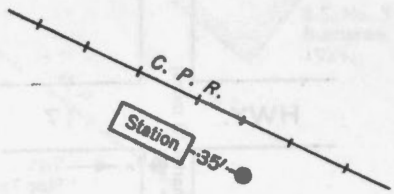
LONG.—81°52.7'
LAT.—46°16.0'
ELEV.—661 ft.
g.—980.6761

SPANISH, ONT.



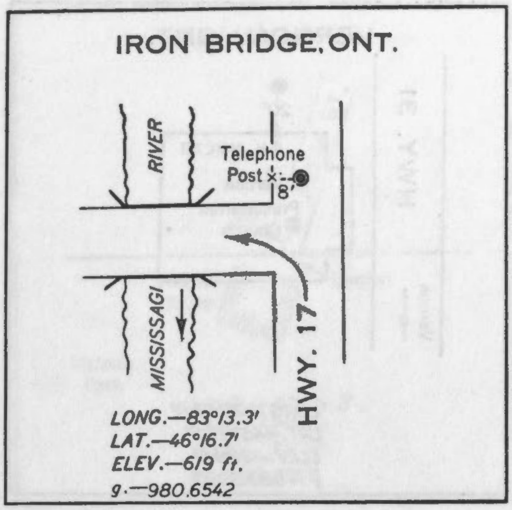
LONG.—82°21.0
LAT.—46°11.6'
ELEV.—610 ft.
g.—980.6575

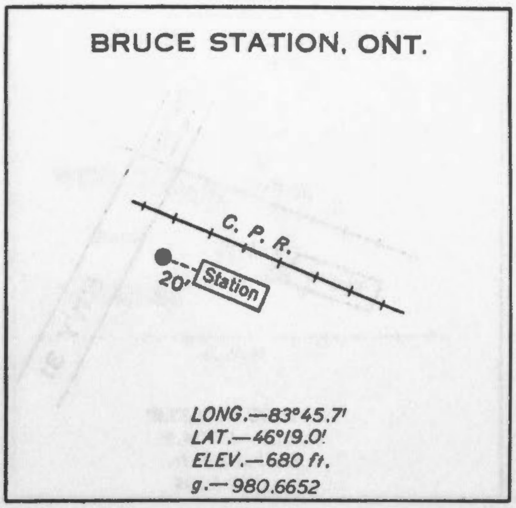
BLIND RIVER, ONT.

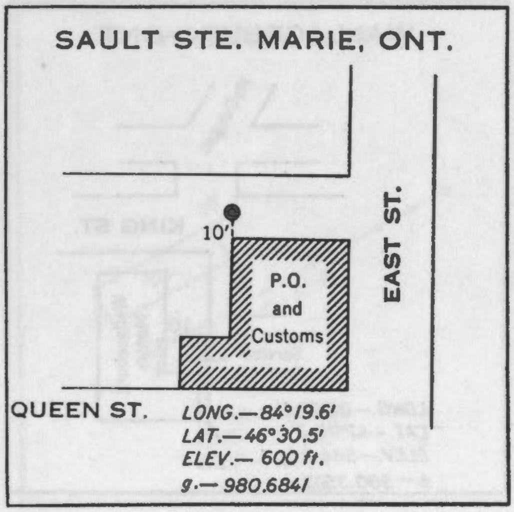


LONG.—82°57.4'
LAT.—46°10.8'
ELEV.—602 ft.
g.—380.6493

HIGHWAY No.17 (CONT'D)







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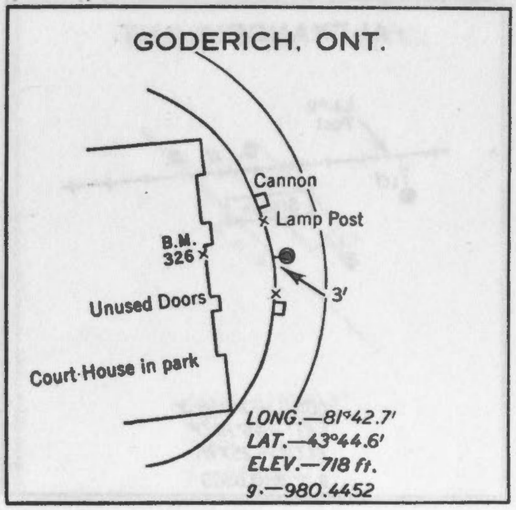

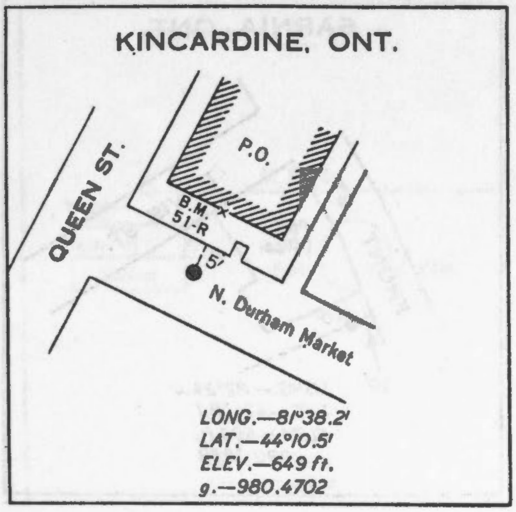

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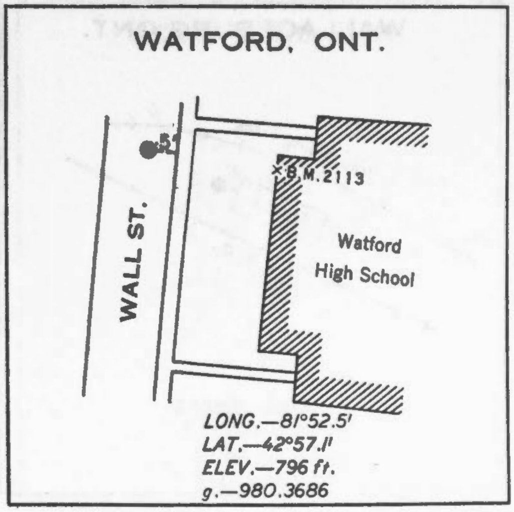

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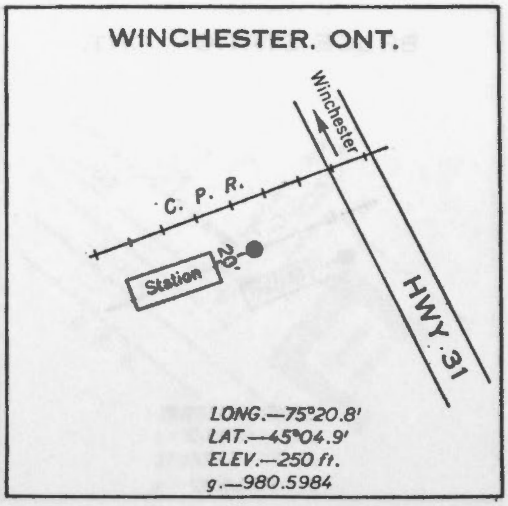

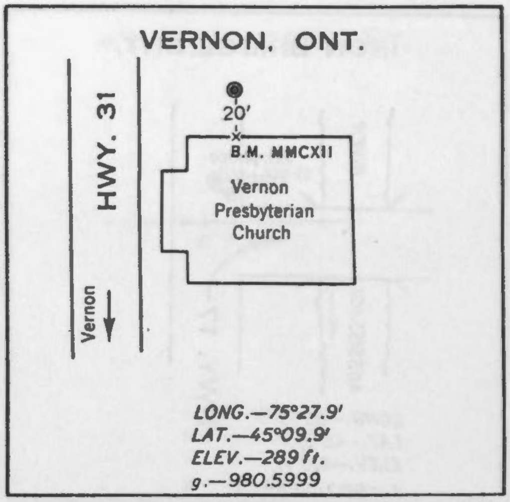

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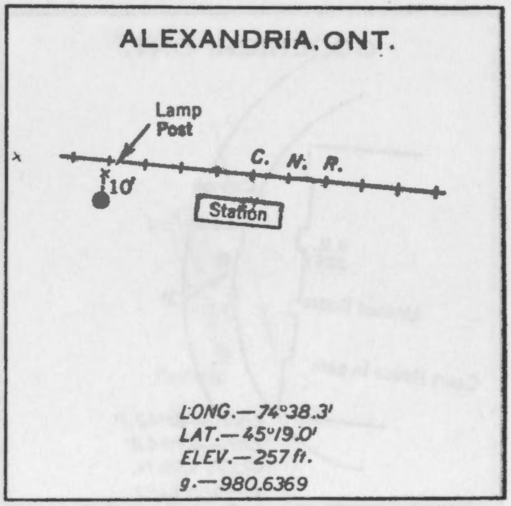

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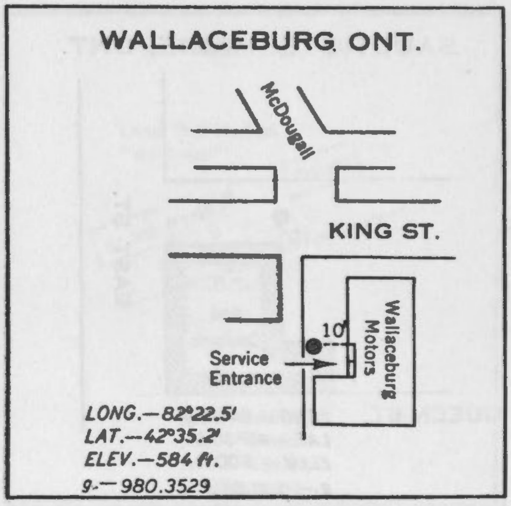

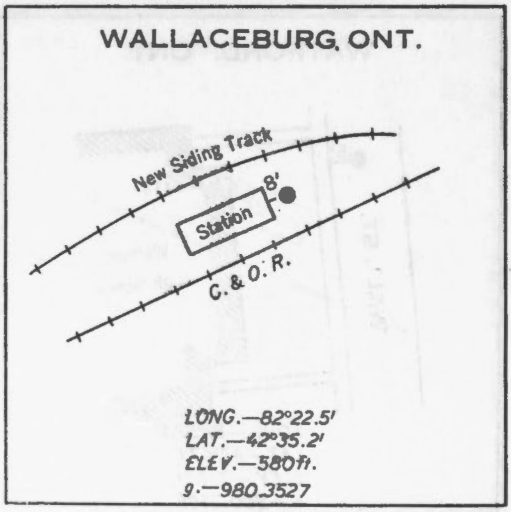

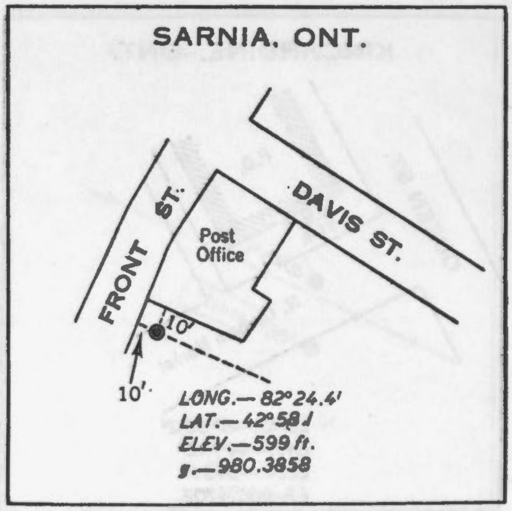

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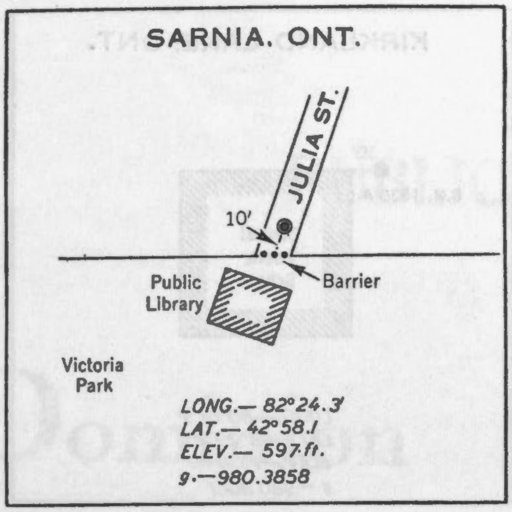

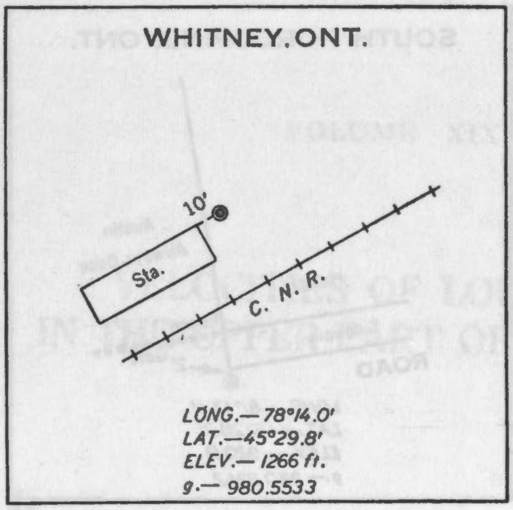

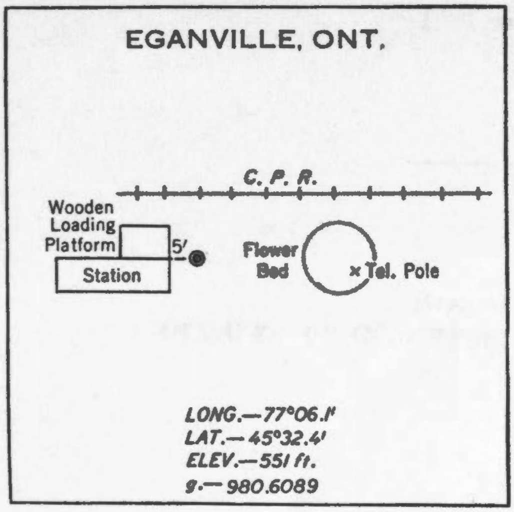

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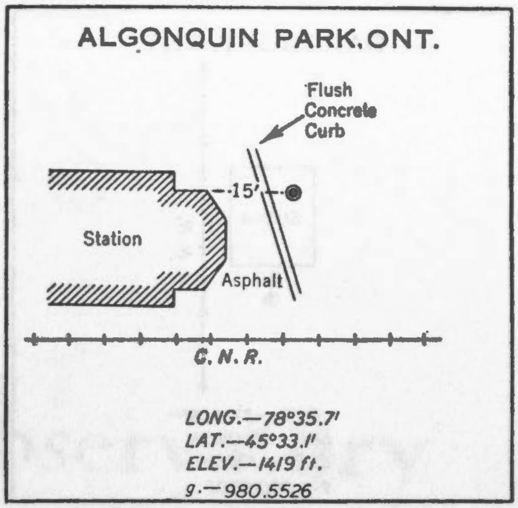
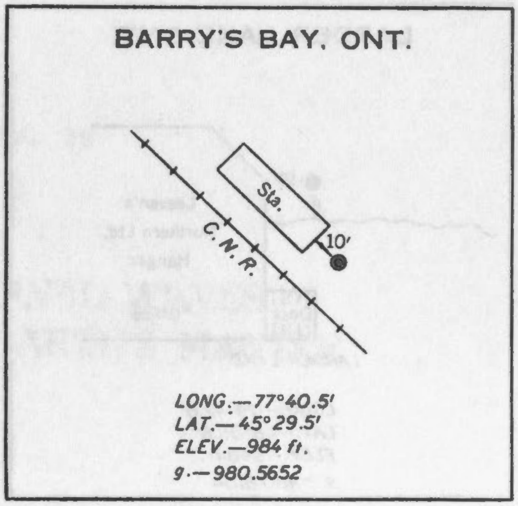
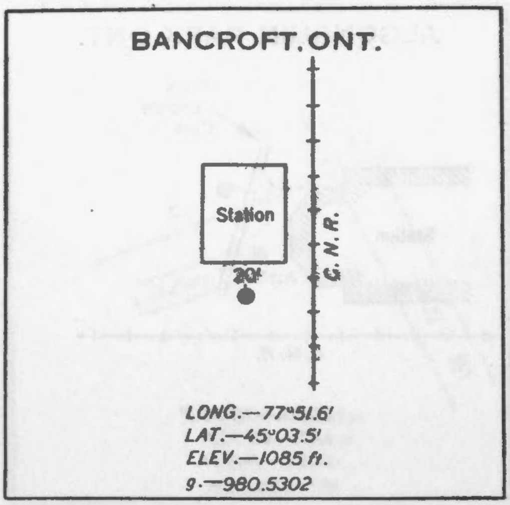
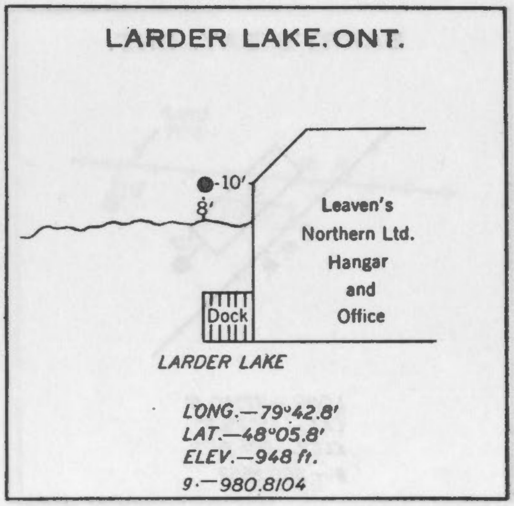


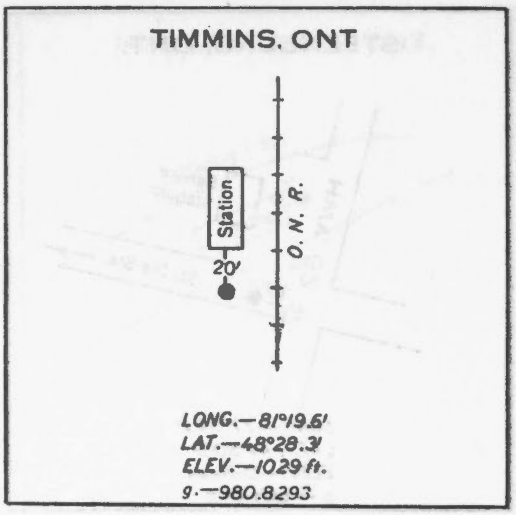


HIGHWAY No. 62

HIGHWAY No.62(CONT'D)







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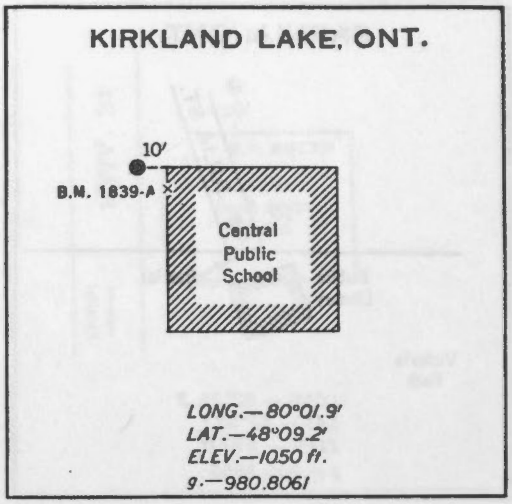

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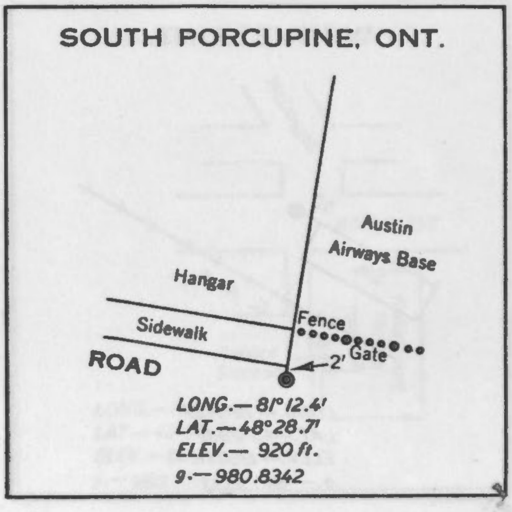
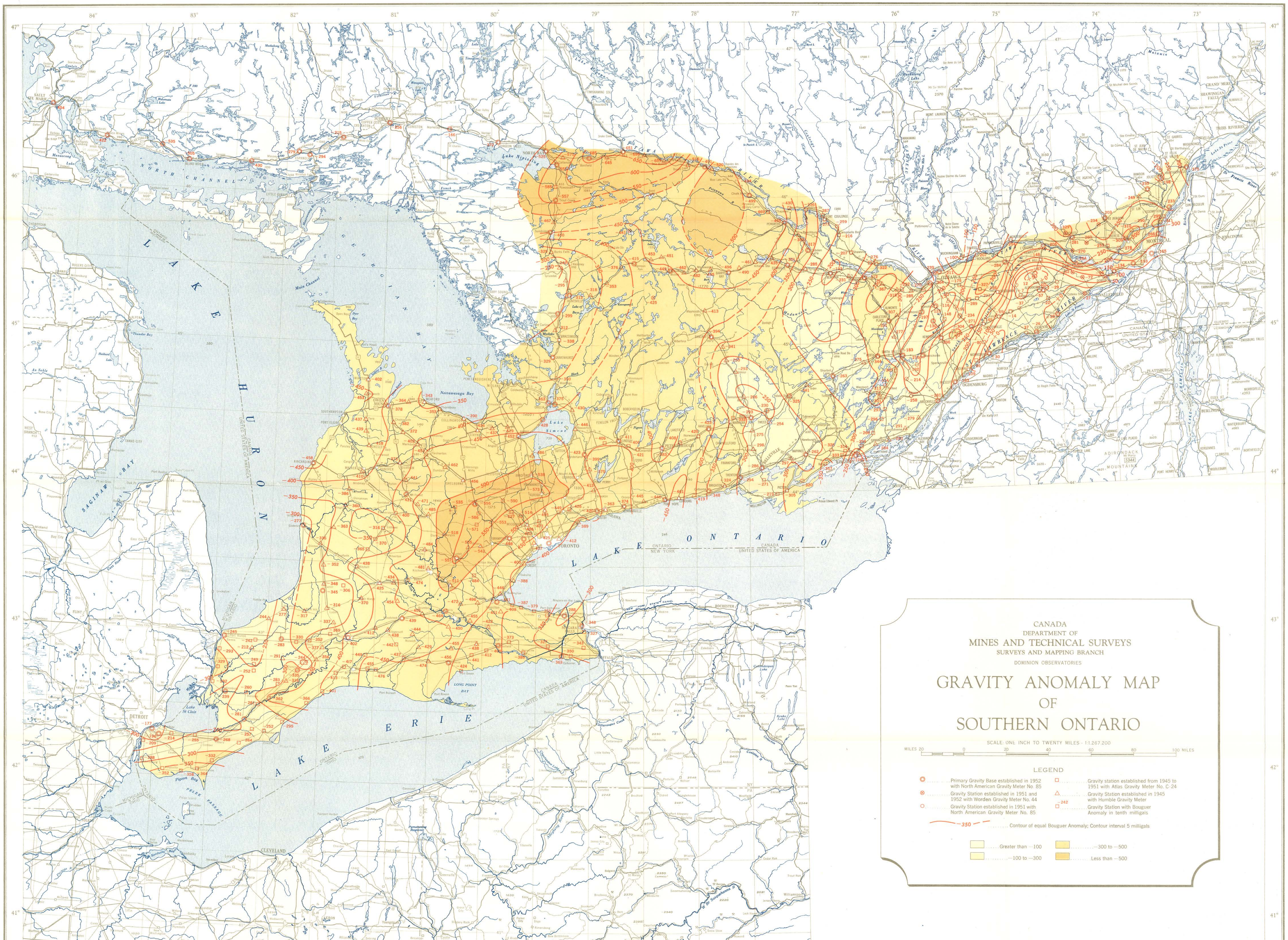
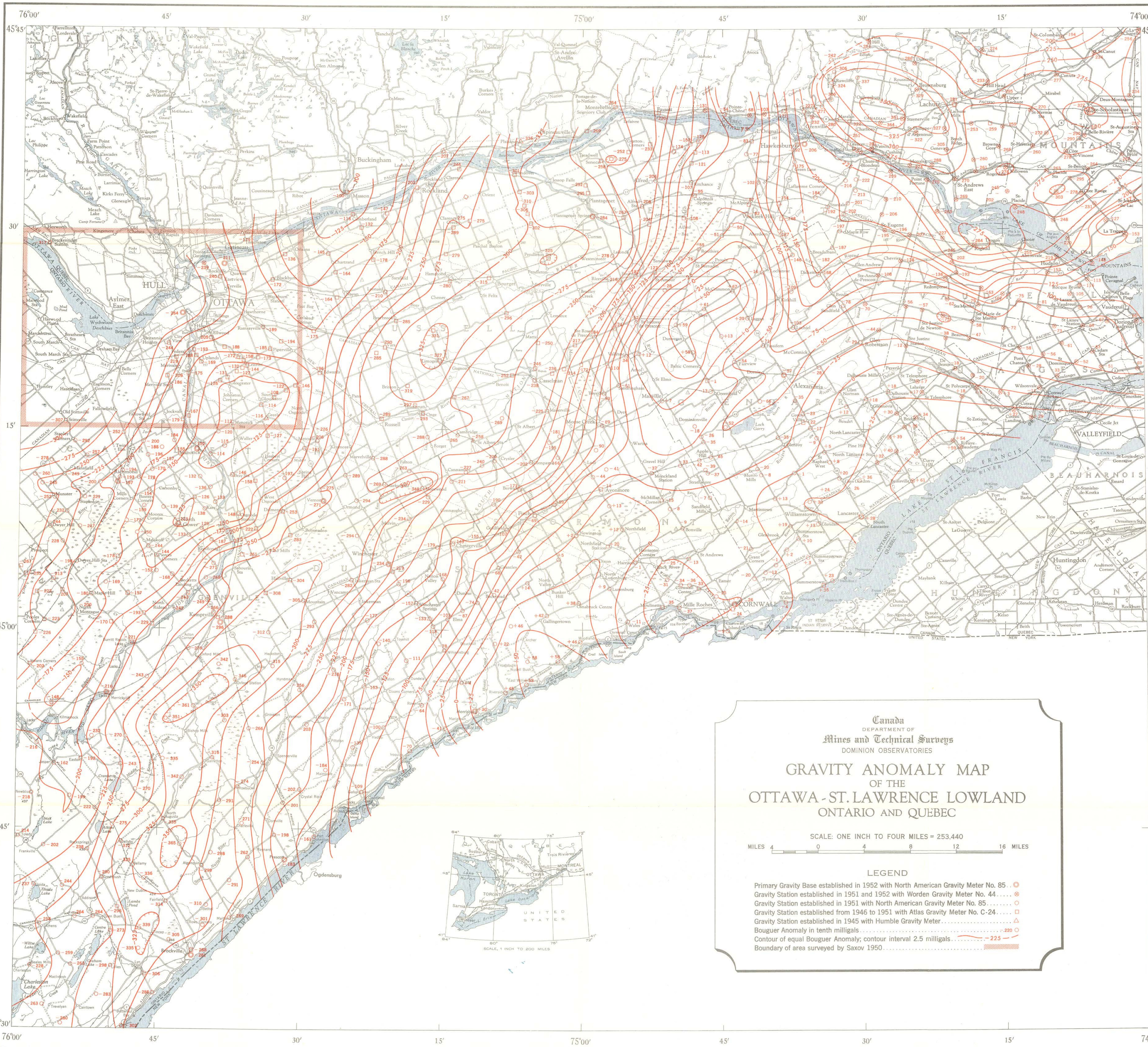




BASE FROM MAPS BY THE DEPARTMENT OF MINES AND TECHNICAL SURVEYS AND THE U.S. COAST AND GEODETIC SURVEY

REPRODUCED AND PRINTED AT THE SURVEYS AND MAPPING BRANCH, OTTAWA, 1955



Base from published maps by Army Survey Establishment,
Department of National Defence and U.S. Army Map Service.

Reproduced and printed at the Surveys and Mapping Branch, Ottawa, 1954

CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
DOMINION OBSERVATORIES

PUBLICATIONS

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Dominion Observatory

OTTAWA

VOLUME XIX No. 10

VELOCITIES OF LONGITUDINAL WAVES IN THE UPPER PART OF THE EARTH'S MANTLE

BY

I. LEHMANN

Reprinted from
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VELOCITIES OF LONGITUDINAL WAVES IN THE UPPER PART OF THE EARTH'S MANTLE

by I. Lehmann

Résumé. — *L'article concerne seulement l'Europe, et rappelle la complexité de sa structure. Puisqu'on admet maintenant que la courbe de propagation des P est une ligne droite jusqu'à 15° environ de distance épicentrale, la vitesse en profondeur ne peut être tirée par une méthode directe ; mais une solution possible peut être obtenue par tâtonnements. Le gradient de vitesse doit être supposé très petit ou nul dans une couche superficielle. On admet que celle-ci atteint 220 km de profondeur et qu'on trouve là un accroissement brusque de la vitesse et du gradient de vitesse. A partir de 15° la courbe P correspond à des ondes réfractées dans la couche inférieure.*

On adopte les vitesses qui figurent dans la Table 2. Jusqu'à 22° la courbe P correspondante est en bon accord avec la courbe de Jeffreys *révisée en 1954.*

On examine les propriétés des courbes P et pP pour les séismes ayant leurs foyers à une certaine profondeur dans la couche supérieure. On étudie quelques séismes profonds de Roumanie ayant tous le même foyer, et l'on compare les durées de propagation des P avec les durées calculées. Quelques écarts semblent ne pouvoir s'interpréter autrement que par des différences locales de structure. On étudie également un séisme profond de la mer Tyrrhénienne.

La solution adoptée correspond à une possibilité, mais elle n'est pas unique et de nouvelles observations sont indispensables. Des déterminations plus précises de la variation d'amplitude seraient particulièrement utiles.

Summary. — *The investigation deals with Europe only and recalls the complexity of its structure. Because the P time-distance curve is now taken to be nearly a straight line up to about 15° epicentral distance, the velocity at depth cannot be derived from it by the direct method, but by trial and error a possible solution is obtainable. The velocity gradient has to be taken quite small or zero in an upper layer. This was taken to extent to 220 km depth and an abrupt increase of velocity and velocity gradient to set in at this depth. From about 15° onwards the P curve becomes associated with waves refracted in the deeper layer.*

The velocities given in table 2 were adopted. Up to 22° the corresponding P curve is in good agreement with Jeffreys' *revised 1954 curve.*

The properties of P and pP curves of shocks having their foci at some depth in the upper layer were considered. Some deep Rumanian earthquakes all from the same focus were examined and their P times compared with those calculated. Some deviations seemed explainable only as due to local differences of structure. A deep earthquake in the Tyrrhenian Sea was also examined.

The adopted solution seems a possible one, but it is not unique and more observations are required. More precise determinations of amplitude variation would be particularly useful.

The constitution of the upper part of the Earth's mantle is a matter of great interest to geophysicists of various fields, and they are hoping for seismology to supply relevant information of a more precise and detailed nature than otherwise obtainable. We observe the transmission times of seismic waves, and are supposed to be able to derive from them the variation of the velocity with depth, which again is a clue to the variation of physical properties.

Time-distance tables were constructed, in particular by GUTENBERG and RICHTER (1934) and by JEFFREYS and BULLEN (1940), and wave velocities were derived from them. It was found, however, that the tables were in error at small distances, and when the necessary corrections were applied wave velocities for the upper mantle could no longer be derived from them. GUTENBERG (1948, 1955) made tentative solutions, but a unique solution is not obtainable. This is due to the fact that the velocity just below the MOHOROVIČIĆ discontinuity is greater than at first assumed, and the curvature of the time-curve up to about 15° so small that the direct method for derivation of the velocity function cannot be applied.

In the course of further studies it was found necessary to distinguish between regions. I shall here consider the European region only.

It was from large explosions that the velocity just below the MOHOROVIČIĆ discontinuity was at first found to be greater than the velocity derived from the JEFFREYS-BULLEN (J. B.) tables. The largest of these, the Heligoland explosion (WILLMORE, 1948), gave us the travel times of P waves out to a distance of 9°; the time-curve was indistinguishable from a straight line of slope 13.6 sec./degree. JEFFREYS, combining this result with some earthquake observations, obtained a corrected P time-curve for Europe (JEFFREYS, 1954).

In recent years numerous large earthquakes were well recorded in Europe at the distances with which I am here concerned. There were a great number of Greek earthquakes and there were also large earthquakes in Algeria. Swiss and other Central European earthquakes were well recorded at the smaller distances. It may seem well worth while to make a study of these earthquakes that are well recorded by a far greater number of stations and with much greater precision than those used in earlier work, and it may seem futile to attempt velocity determination before this has been done.

It is undoubtedly desirable that a comprehensive study of recent European earthquakes should be made. It is not likely, however, to prove so very straightforward. Most of the earthquakes occur in outlying regions, where epicentre determinations are uncertain. On the other hand a great number of stations are in small azimuthal sectors and, therefore, should yield reliable slopes of the time-curves. This is on the supposition that the first wave observed is the same everywhere. It may seem as if we could rely on the first P wave being recorded at the now numerous stations equipped with sensitive short-period seismographs. However, in his study of intermediate earthquakes GALANOPOULOS (1953) mentions that shallow Greek earthquakes, even very large ones, in contrast to the intermediate earthquakes have very small first P waves, and that the subsequent movement increases gradually. It may, therefore, seem uncertain that it is possible to pick up the onset of the same wave everywhere, and if we cannot rely upon this the observations are not very useful for the construction of time-curves. Also, European structure may not be so homogeneous as we would like and Eurasiatic structure less so. We know the composition of the crust to vary a great deal, and the depth of the Mohorovičić discontinuity is believed to be at somewhat varying depth. Also, we have in Rumania earthquakes at a depth of about 150 km, showing that the mantle is not in a stable state there. Peterschmitt (1956) has found that the Calabrian arc has properties similar to those of the Pacific arcs. A deep earthquake has occurred in the region and several intermediate ones. We have had a very deep earthquake with its epicentre in Spain. All of this points to considerable structural differences in the mantle underlying Europe. It does not reduce the interest attached to a comprehensive study of European earthquakes, on the contrary, but it makes it somewhat doubtful that precise results applying to the whole of Europe are obtainable.

The P time-curve as we have it now (Jeffreys, 1954) may not be the best approach to a mean time-curve for Europe, but certain of its features are not likely to be greatly modified in future studies. The small or negligible curvature up to about 15° epicentral distance and an appreciable curvature from there onwards are likely to be maintained. The corresponding velocity function necessarily differs considerably from that derivable from the J. B. time-curve, and it is of some interest to see in what respects it differs from it. We cannot actually determine the velocity function, but we can arrive at some of its characteristic features. We can assume a velocity function having these features, derive the time-curve from it and alter the assumption until a good fit to observations is obtained. The velocity function arrived at in this way is one of the many possible solutions, and it may help us to see what kind of solution can be considered.

On a previous occasion I worked out a tentative solution (Lehmann, 1956) but I have now worked out results more precisely. The time-curve I attempted to approximate was taken to be a straight line of slope 13.6 sec./degree up to 15° epicentral distance and to start to bend there. The difference of the heights at 15° and 22° was taken to be the same as that of the J. B. curve for a surface focus.

The velocity function taken was the one first used by A. Mohorovičić (1910) when he attempted to determine the depth of his discontinuity. In later years Bullen (1945) has drawn attention to the formula that may be written

$$v = ar^{-k} = v_0 \left(\frac{r}{r_0}\right)^{-k}, \qquad (1)$$

where v is the velocity at distance r from the centre of the sphere to which the formula is applied, the subscript $_0$ indicates surface values, and a and k are constants.

When computations are involved the formula is easier to work with than the WIECHERT formula $v = a - br^2$, while this latter formula lends itself more easily to construction since the rays are circular arcs.

Since it may come useful to others intending to do similar work, I shall go into some detail about how the formula is applied.

The epicentral distance at which a ray of constant $\alpha = \frac{r}{v} \sin i$ emerges is

(2) $$\Delta = 2\alpha \int_{r_u} \frac{1}{r} \frac{1}{\sqrt{u^2 - \alpha^2}} dr$$

where $u = \frac{r}{v}$ and r_u is the distance from the centre to the deepest point of the ray. We have :

(3) $$\alpha = \frac{r_u}{v_u} = \frac{r_0}{v_0} \sin i_0 = \frac{dt}{d\Delta},$$

where t is travel time to distance Δ when Δ is measured in radians, or $\alpha = \frac{dt}{d\Delta} \cdot \frac{180}{\pi}$ when Δ is measured in degrees. From (1) we find

$$u = \frac{1}{a} r^{k+1},$$

and substituting this in (2) we find :

$$\Delta = 2 \int_{r_u}^{r_0} \frac{1}{r} \frac{1}{\sqrt{\frac{1}{a^2 \alpha^2} r^{2(k+1)} - 1}} dr.$$

Putting

$$x = \frac{1}{a\alpha} r^{k+1}, \quad \frac{dx}{x} = \frac{k+1}{r} dr,$$

we find

$$\Delta = \frac{2}{k+1} \int_{x_u}^{x_0} \frac{1}{\sqrt{x^2 - 1}} \frac{dx}{x}$$

and obtain :

$$\Delta = \frac{2}{k+1} [\sec^{-1} x]_{x_u}^{x_0} = \frac{2}{k+1} \left[\sec^{-1} \frac{1}{a\alpha} r^{k+1} \right]_{r_u}^{r_0};$$

(1) and (3) give us :

$$\frac{r_0}{v_0} = \frac{r_0^{k+1}}{a} \text{ and } \frac{r_u}{v_u} = \alpha = \frac{r_u^{k+1}}{a},$$

and therefore

(4) $$\cos \frac{k+1}{2} \Delta = \frac{\alpha}{u_0}.$$

From $\alpha = \frac{dt}{d\Delta} = u_0 \cos \frac{k+1}{2} \Delta$ we find :

(5) $$t = u_0 \frac{2}{k+1} \sin \frac{k+1}{2} \Delta.$$

From (4) and (5) we obtain Δ and t for any $\alpha \leqslant u_0$ when the surface velocity v_0 and the constant k are known. We proceed as follows. $\frac{dt}{d\Delta}$ (Δ measured in degrees) is taken as independent variable ; it is multiplied by $\frac{180}{\pi}\frac{1}{u_0}$ to give $\cos\frac{k+1}{2}\Delta$. From a trigonometrical table $\frac{k+1}{2}\Delta$ and $\sin\frac{k+1}{2}\Delta$ are obtained and from these Δ and t are found. The calculations are conveniently carried out in a table under the following headings :

$\frac{dt}{d\Delta}$	$\cos\frac{k+1}{2}\Delta$	$\sin\frac{k+1}{2}\Delta$	$\frac{k+1}{2}\Delta$	Δ	$t.$

We may wish to find the r_u and v_u corresponding to a given value of $\frac{dt}{d\Delta}$. We have $\frac{r_u}{v_u} = \alpha$ and $v_u = ar_u^{-k}$ hence

$$r_u^{k+1} = a\alpha, \tag{6}$$

and

$$\log r_u = \frac{1}{k+1}(\log a + \log \alpha), \tag{7}$$

$$\log v_u = \frac{1}{k+1}(\log a - \log \alpha). \tag{8}$$

From (6) we can also find the α and $\frac{dt}{d\Delta}$ of the ray having a given r_u.

As a rule the velocity formula is taken to be valid only down to a certain depth r_1 and at this depth the k and possibly also the v changes. The problem is then to find the $[\Delta, t]_{0,1}$ for transmission through the layer $[r_0, r_1]$. Take (Δ_0, t_0) to be the (Δ, t) as found for the sphere of radius r_0 with surface velocity v_0 for $k = k_0$; $(\Delta_{0,1}, t_{0,1})$ the $(\Delta\, t,)$ of a sphere with radius r_1, surface velocity $v_1 = a_0 r_1^{-k_0}$ for $k = k_0$. Then $[\Delta, t]_{0,1} = (\Delta_0 - \Delta_{0,1},\ t_0 - t_{0,1})$. It is to be noted that k has to be taken $= k_0$ also in the sphere of radius r_1 since $v = v_0\left(\frac{r}{r_0}\right)^{-k} = v_1\left(\frac{r}{r_1}\right)^{-k}$.

We have (1)

$$v = ar^{-k},$$

$$\log v = \log a - k \log r,$$

$$\frac{dv}{dr} = -k\frac{v}{r} = -akr^{-k-1}. \tag{9}$$

Hence v increases with decreasing r when k is positive and is constant for $k = 0$.

**

When $k < 0$ v decreases with decreasing r and for $k = -1$ we have $\frac{dv}{dr} = \frac{v}{r}$ which marks critical decrease of velocity. Thus for $k \leqslant -1$ the rays do not emerge. This is easily seen in another way for we obtain from (1)

$$\frac{r}{v} = \frac{r^{k+1}}{a},$$

or for $k = -1$

$$\frac{r}{v} = \frac{1}{a},$$

and since $\alpha = \frac{r}{v} \sin i$, $\sin i$ and i remain constant for a given α. The ray therefore is a logarithmic spiral. Since

$$\alpha = \frac{r^{k+1}}{a} \sin i,$$

we see that for $k < -1$ $\sin i$ and i decrease with decreasing r; the ray therefore goes down into the earth more and more steeply and it never emerges.

When $k \leqslant -1$, Δ and t can still be obtained from our formulae (4) and (5), but they become negative and are therefore without physical meaning. However, u being greater than u_0, $\Delta_{0,1}$ and $t_{0,1}$ are numerically greater than Δ_0 and t_0 and the $\Delta_0 - \Delta_{0,1}$ and $t_0 - t_{0,1}$ are positive. The $[\Delta, t]_{0,1}$ for transmission through the layer r_0, r_1 can therefore be obtained in the usual way. Since layers in which the rate of decrease of velocity is greater than critical are supposed to exist, it is of some importance to be able to calculate times of transmission through them on simple velocity assumptions.

As said already, calculations become more involved when the WIECHERT formula $v = a - br^2 = v_0 - b\,(r^2 - r_0^2)$ is taken than when the formula $v = ar^{-k}$ is used. We derive from it:

$$\text{(10)} \qquad \cot i \cot \frac{\Delta}{2} = \lambda,$$

where λ is a constant $= \frac{2r_0^2\, b}{v_0} + 1 \geqslant 1$ provided $b \geqslant 0$ and

$$\text{(11)} \qquad t = 2\alpha \frac{1}{\sqrt{\lambda^2 - 1}} \text{arc sin} \left(\sqrt{\lambda^2 - 1} \sin \frac{\Delta}{2}\right),$$

Taking again $\frac{dt}{d\Delta}$ as independant variable we find

$\sin i = \frac{dt}{d\Delta} \frac{180}{\pi} \cdot \frac{1}{u_0}$ and thereafter $\cot i$ and from (10) $\cot \frac{\Delta}{2}$ and Δ. We then successively find $\sin \frac{\Delta}{2}$, $\sqrt{\lambda^2 - 1}\, \sin \frac{\Delta}{2}$, $\text{arc sin} \left(\sqrt{\lambda^2 - 1}\, \sin \frac{\Delta}{2}\right)$ and t. If the calculations are carried out in a table similar to the one on p. 385, this table has to have 9 columns. When the $(\Delta, t)_{0,1}$ for transmission through the layer (r_0, r_1) are wanted we have to use different values of λ in the two spheres while k remained unaltered, for we have

$$\lambda_0 = \frac{2r_0^2 b}{v_0} + 1 \qquad \lambda_1 = \frac{2r_1^2 b}{v_1} + 1.$$

We shall now attempt to approximate our P curve, calculating it on certain velocity assumptions. The time distance curve we wish to approximate is much more straight than the J. B. curve up to an epicentral distance of about 15°. Our velocity increase in the corresponding layer is therefore necessarily smaller. Corresponding to the J. B. curve the velocity increases from 7.75 km/sec just below the MOHOROVIČIĆ discontinuity to 8.32 km/sec at 220 km depth where the ray emerging at 15° epicentral distance has its deepest point. When there is a smaller velocity increase the rays are more shallow, and when the velocity increase is small enough to make the curve up to 15° seem nearly straight, the ray emerging at 15° cannot come down to a depth much greater than 120 km. This is to say that we have to assume either that the velocity increase responsible for the bend that begins at 15° epicentral distance sets in at a depth not much greater than 120 km or else that the time-curve from 15° onwards is not the continuation of the curve at smaller distances but is a different branch due to a wave refracted in a deeper layer. This latter possibility was considered in my earlier study, but I regard it as a certainty now, for a strong velocity increase cannot be taken to set in at a depth of about 120 km. The chief evidence comes from GUTENBERG'S determination of the velocity at the focal depth of large earthquakes (GUTENBERG, 1953). The velocities found for depths smaller than 200 km vary a great deal, but a marked increase of velocity with depth does not occur until at depths exceeding 200 kms. I have tentatively taken the boundary to be at 220 kms depth.

This leaves us with a layer about 100 km deep from which no rays are observed to emerge in shallow shocks. If they were observable they would be associated with a time-curve of slight curvature forming the continuation of the straight line up to 15°. This is to say that no direct information about the velocity variation in the layer between, say, 120 and 220 kms is obtainable from observations of shallow shocks. Some further information should be obtainable from deep shocks having their foci in the layer, but as we shall see later, even deep shocks will not supply information for depths exceeding about 160 kms.

I calculated the P curve taking the velocity in the crust to be constant = 6.3 km/sec. This is not quite correct, but it makes very little difference to the time-curve for greater distances. Below the MOHOROVIČIĆ discontinuity the velocity was taken to increase rather strongly from 8.0 to 8.12 km/sec. in a layer 20 km deep, and to remain constant from there down to the 220 km level. The deepest ray in the uppermost layer emerges at a distance of 4°6. The strong velocity increase was assumed because amplitudes are found to be relatively large at small distances and to decrease rapidly later on. Actually it may not be necessary to assume a strong velocity increase at small depth in order to account for the large amplitudes since the laws of ray optics do not hold close to a boundary. However, supposing these laws to hold deeper down, at the depths in question, the strong and sometimes rather sudden decrease of amplitudes beyond about 5° is easily accounted for, since the rays are widely spread when they enter a layer of constant or nearly constant velocity from a layer in which there is a much stronger velocity increase. There will be a decrease of energy that may well come near to producing a shadow zone. In my example I had $\frac{dt}{d\Delta} = 13.57$ sec/degree at 5° epicentral distance and 13.50 sec/degree at 15°. Thus the bundle of rays responsible for that part of the time-curve is exceedingly small, so small indeed that there may not be any observations at all except, perhaps, in very large earthquakes. It may be necessary to assume some increase of velocity in the lower layer to account for the observations obtained. However, only a small increase of velocity is possible if the time-curve is to be nearly straight and when transmission times only, not amplitudes, are considered it makes very little difference to the results whether the velocity is taken to increase slightly, to be constant or to decrease slightly. The simplest assumption, that of constant velocity, was therefore maintained.

The ray having its deepest point at the 220 km level then emerges at an epicentral distance of 28°3. The time-curve associated with the rays transmitted in the layer has a slight curvature, the slope at the end-point being 13.22 sec/degree.

We now had to find a velocity function in the lower mantle, below the 220 km level, that would produce a branch intersecting the first branch at about 15° epicentral distance and bending so that the difference of height at 15° and 22° would be the same as for the J. B. curve.

Various attempts were made. At first the velocity at 220 km depth was retained and an abrupt increase of velocity gradient assumed. It resulted in a time-curve having a loop with its lower end at a distance not much smaller than 15°. There was a concentration of energy at the turning point that would necessarily give rise to large amplitudes and since exceptionally large amplitudes are not observed at this distance the assumption was abandoned. An abrupt increase in the velocity itself as well as in velocity gradient was then assumed. Again various attempts were made. The final assumption adopted was that of an increase of velocity from 8.12 km/sec to 8.40 km/sec. at the 220 km boundary and a strong velocity gradient below. In the formula $v = v_0 \left(\frac{r}{r_0}\right)^{-k}$ k was taken = 3. It resulted in a time-curve that up to 22° deviated only very slightly from JEFFREYS' final time-curve of 1954 (see table 1). It has a slightly smaller slope below 15° since JEFFREYS (rather arbitrarily as he remarks) adopted the slope 13.66 sec/degree while my average slope is 13.54 sec/degree. JEFFREYS' time exceeds mine by $0^s.4$ at 2° and the deviation increases to $1^s.7$ at 15°. From 17° to 22° the difference does not exceed a few tenths of a second.

TABLE 1

TRAVEL TIMES OF P WAVES

Δ	*t*. H. J.		*t*. I. L.	
0	m	s	m	s
2		35.0		34.6
4	1	2.4	1	2.0
6		29.8		29.1
8		57.1		56.3
10	2	24.4	2	23.4
11		38.1		36.9
12		51.7		50.5
13	3	5.4	3	4.0
14		19.0		17.5
15		32.7		31.0
16		45.5		44.5
17		57.9		57.8
18	4	10.0	4	9.7
19		21.8		21.5
20		33.2		32.8
21		44.1		43.9
22	4	54.7		54.6

The intersection of my two branches occurs at 17° instead of at 15° as was intended, but the two branches are very close to one another at 15°, only slightly more than 1^s apart, and the increase of amplitude that seems to take place at about that distance could be due to the wave associated with the second branch.

The velocities derived from the J. B. time-curve (JEFFREYS 1939, p. 511) and my velocities are compared in table 2. JEFFREYS' velocity in the upper part of the mantle is at first smaller than the one here assumed, but it increases so as to reach the same value at 159 km. depth and thereafter becomes greater. At 220 km depth the increase of my velocity makes it become greater than that of JEFFREYS, and it remains greater down to somewhere between 412 and 476 kms

TABLE 2

VELOCITIES OF P WAVES

DEPTH R	VEL. H. J. km/sec	DEPTH km	VEL. I. L. km/sec
0.00	7.75	35	8.00
		55	8.12
.01	7.94	95	8.12
.02	8.12	159	8.12
.03	8.32	220	8.12
		220	8.40
.04	8.56	286	8.68
.05	8.76	349	8.95
.06	8.96	412	9.24
.07	9.52	476	9.54
.08	9.88	539	9.86
.09	10.28	602	10.18
.10	10.53	666	10.53
.11	10.77	729	10.89
.12	10.99	793	11.26

depth, where JEFFREYS velocity increase sets in. From there down to the 666 km depth the velocities are equal. Below that depth my velocity increases more strongly than that of JEFFREYS', but there the velocity formula is no longer applicable since the rate of increase of the actual velocity decreases as is indicated by a straightening of the time-curve and diminishing amplitudes from about 22° epicentral distance.

Up to that distance our solution seems quite satisfactory and the corrected J. B. curve can be joined on to it there.

The question is now whether or not other results derivable on our assumptions are in agreement with observations.

We can calculate time-distance curves for foci at varying depth, but in Europe there are not many shocks deeper than normal with which we can compare. There are intermediate shocks in the Aegean Sea and near Crete, but as a rule the epicentres cannot be well determined and the depths found for them have great uncertainty. I have tried to use the observations of some of them, but they scattered too widely. However, in Rumania several large earthquakes occurred at a depth supposed to be about 150 km. Their epicentres should be determinable with a fair degree of accuracy. They have been very well observed by a considerable number of stations in the range of distance in which we are interested.

I shall compare the observations of the Rumanian shocks with time-curves calculated on our velocity assumptions, but before doing so we may consider in a general way some of the implications of these assumptions.

The P time-distance curves calculated for foci in the upper layer of the mantle, i.e. above the 220 km level, all have two branches as has the P curve for a surface focus, and the points of intersection of the branches will be at a smaller epicentral distance the greater the depth of focus.

The branches associated with the direct waves, for which the rays are entirely above the 220 km level, have inflexion points at the distances where the rays starting horizontally at the focus meet the surface of the earth ; they are at greater epicentral distances the greater the focal depth. They are at greater distances than the corresponding J. B. inflexion points since the rays bend less. The branches are very nearly straight lines from the inflexion points onwards and also for some distance below. The slope of the line depends on the velocity at the depth of focus. The line is intersected by the curved branch due to the refracted wave and for distances greater than that of the point of intersection the direct wave is not likely to be observable, so the line would be cut off, so to speak, and this would happen at a smaller epicentral distance the greater the focal depth. For focal depth 160 km the point of intersection is very close to the inflexion point, at 11°.5. The time-curve, however, has still an almost straight section extending from about 5° to 11°.5 and the slope of this section will be close to that at the inflexion point. For greater depth the straight section will become smaller and its slope will deviate slightly from that at the point of inflexion. It would become increasingly difficult to determine the slope from observations.

We remarked on the fact that when the velocity was very nearly constant in the upper mantle, no ray from a surface focus penetrating deeper than to about 120 km would be seen to emerge at the surface. We now find that in deep focus earthquakes we shall be able to observe the emergence of rays having their deepest points down to about 160 km, but not below that depth. Thus no direct information about the variation of the velocity between 160 km and 220 km depth is obtainable from observations.

We have taken the velocity to be constant in the upper mantle. It is not unlikely that instead it increases slightly. If so, the inflexion points will be at somewhat smaller distances. Taking the velocity to increase from 8.12 km/sec to 8.2 km/sec. at 220 kms depth the inflexion point for a focus at 100 kms depth will be at 7°2 epicentral distance instead of for constant velocity at 8°.2 and the inflexion point for 220 km depth will be at 12°.1 instead of at 14°.1.

Since our velocity in the upper mantle is at first greater than the J. B. velocity and it increases less with depth, the straight part of the time-curves have smaller slopes than the J. B. curves for small depth of focus, but the slopes decrease less with depth and for 160 km focal depth the slopes are equal.

The pP curves calculated on our velocity assumptions also have two branches. The pP and PP curves have their common starting point at the distance reached by the ray leaving the focus horizontally and reflected at the surface of the earth. This point will be at a considerably greater epicentral distance than that of the J. B. tables because the rays are more straight. The pP curve at first goes backwards a little way, stays at a focal point and then goes forward (see Bullen, 1955 and note at end). When the P ray forming part of pP meets the 220 km boundary and is refracted the pP emerges at a much shorter epicentral distance than the « first » pP ray.

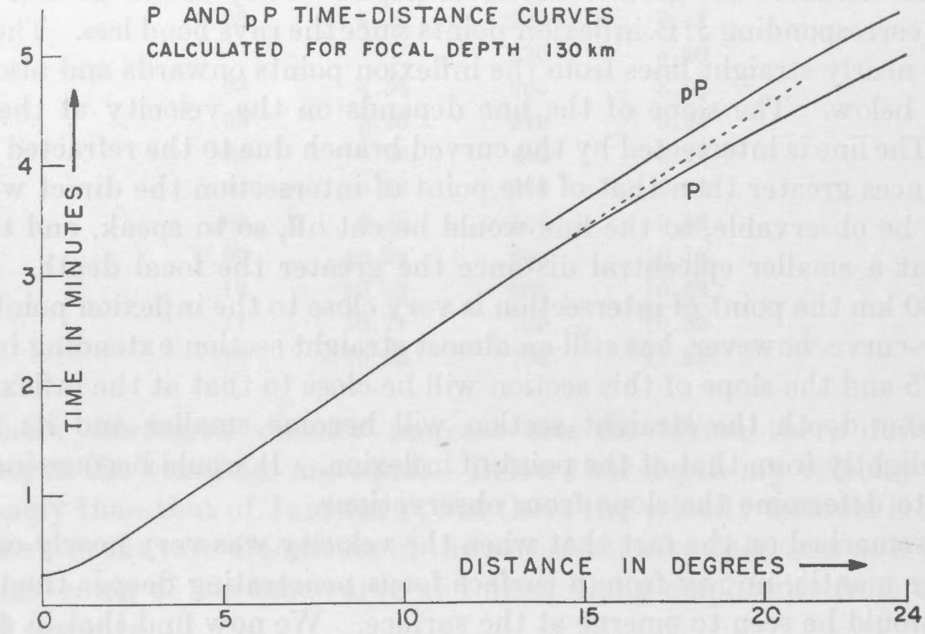

FIG. 1.

In figure 1 are seen the two branches of the P curve calculated for focal depth 130 km and the branch of the refracted pP. The two P branches intersect close to 13° epicentral distance so that is where the curve begins to bend. The inflexion point is at distance 10°.1. The first point of the pP curve is at 30°.3 epicentral distance, 63^s above P, and the focal point is close to this point at a slightly smaller distance. The second branch, the one plotted in the figure, has its lowest point at 14°.1, 16^s above P. pP—P, however, increases rapidly with distance and at 24° is 25^s or 2^s smaller than the J. B. pP—P. The smallest distance at which PP appears is about 20° and there it is 10^s later than pP.

The J. B. pP and PP would have their common starting point at a distance of approximately 17° and about 16^s after P. There would be a focal point with large amplitudes close to this point. This does not seem to have been observed and, indeed, cannot be present at so small an epicentral distance when the velocity gradient in the upper mantle is small.

We shall now consider the Rumanian earthquakes.

The earthquake of 1929, Nov. 1, was used by H. JEFFREYS (1935) when he determined corrections to the original J. B. tables by means of observations of deep focus earthquakes. He corrected the I. S. S. epicentre and found the point 45°.88 N 26°.48 E. The depth he fixed at 142 km ± 8 km.

In the Seismicity of the Earth (GUTENBERG and RICHTER, 1954) 14 Rumanian earthquakes all from approximately the same focus are listed. They are listed in Table 3. The epicentres and depths are those given in the Seismicity of the Earth and in the International Seismological Summary. M is magnitude according to GUTENBERG and RICHTER. The numbers of P (and P′) and the greatest distances at which they were recorded are taken from the I. S. S. For the earthquakes N^os^ 6, 9 and 13 two distances are given, there being many observations out to the smaller distances and just a few at much greater distances.

P was well recorded by many stations in 8 of these earthquakes viz. in N^os^ 1, 3, 4, 7, 8, 10, 13, 14. When the transmission times as given in the I. S. S. were taken and corrected for differences in origin time, the times of individual stations of N^os^ 1,3, 7, 8, 10 and 14 were found to vary very little. Those of N° 4 differed systematically from the others and random errors were rather large in N° 13.

The stations selected were those recording the earthquake of 1948, May 29. Most of these stations also recorded the two large earthquakes of 1940, Oct. 22 and Nov. 10, and there was excellent agreement between the corrected transmission times, also at the greatest distances where the transmission times of Tinemaha at distance 91°.8 for the three shocks were practically the same and those of Mount Wilson (94°.1) also. There can be no doubt about these three shocks having the same focus. Comparison with the other shocks was not quite so effective because they were not recorded at all the same stations. Thus the most distant stations recording the 1934 shock were not in operation in 1940 and 1948. The 1929 shock was recorded by 19 stations at distances between 6° and 11° but only 5 of these operated in 1940, and in 1929 there were 21 observations between 11° and 15° while in 1940 there were 18 and about half of them were not the same. However, where comparison was possible agreement was so close that there can be no doubt about the 6 shocks mentioned and marked by a cross in the table all having the same focus.

Mean values of the observations of individual stations were formed for distances up to 25°. Mean deviations m_2 of the means were also determined and when these were smaller than or equal to 1^s the station and its mean value was retained for further work and entered in table 4. 7 of the stations had mean deviations $0^s.2$ or smaller ; that of Basel is 0^s, but it has been put in parenthesis because

TABLE 3

RUMANIAN EARTHQUAKES

No	Date	Hour	Epicentre G and R	Epicentre I. S. S.	Depth G and R	Depth I. S. S.	M	Nos. of P Reported	Greatest Distance °
1×	1929 Nov. 1	6	45.9 N 26.5 E	46.0 N 26.1 E	150 km	n	5 3/4	68	46.9
2	1934 Feb. 2	19	45 N 26 E	45.7 N 26.1 E	»	n	5 1/4	18	18.2
3×	» Mar. 29	20	45 3/4 N 26 1/2 E	45.8 N 26.5 N	»	n	6 1/4	75	69.3
4	1935 July 13	0	46 N 26 1/4 E	46.2 N 26.5 E	»	n	5 1/4	40	35.3
5	1938 July 13	20	45 3/4 N 26 3/4 E	45.7 N 26.8 E	»	.025 R	5 1/4	32	23.7
6	1939 Sept. 5	6	45 3/4 N 26 1/2 E	» »	»	.010 R	5 1/4	25	23.7/94.3
7×	1940 June 24	9	45 3/4 N 26 3/4 E	» »	»	n	5 1/2	39	29.9
8×	» Oct. 22	6	45 3/4 N 26 1/2 E	» »	»	.010 R	6 1/2	79	94.7
9	» Nov. 8	12	45 1/2 N 26 E	» »	»	»	5 1/2	15	16.2/93.
10×	» Nov. 10	1	45 3/4 N 26 1/2 E	» »	»	»	7.4	139	156.4
11	» Nov. 11	6	46 N 26 3/4 E	» »	»	»	5 1/2	25	33.9
12	» Nov. 19	20	46 N 26 1/2 E	» »	»	»	5 1/4	13	16.6
13	1946 Nov. 3	18	45 3/4 N 26 1/2 E	» »	»	»	5 1/2	41	32.2/91.2
14×	1948 May 29	4	46 N 26 3/4 E	» »	»	.015 R	5 3/4	60	94.3

TABLE 4

6 RUMANIAN EARTHQUAKES

MEAN VALUES OF THE TRANSMISSION TIMES OF P
COMPARED WITH CALCULATED TIMES, DEPTH 130 KM.

STATION	DISTANCE	AZIMUTH	P OBS.		m_2	O-C
	°	°	*m*	*s*	*s*	*s*
Bucharest	1.45	198	0	25.5	0.6	—1
Sofia	3.9	221	0	56.0	1.0	—1
Istanbul	5.1	160	1	11.5	1.0	—2
Budapest	5.5	291	1	17.4	.9	—1
Warsaw	7.4	332	1	45.3	.2	2
Trieste	9.0	275	2	5.6	.7	0
Prague	9.2	303	2	10.2	1.0	2
Rome	10.9	255	2	28.3	.2	—2
Potsdam	11.0	312	2	31.8	.2	0
Jena	11.2	303	2	35.2	.5	1
Chur	11.85	282	2	42.5	.4	1
Moscow	12.1	30	2	47.0	.9	0
Stuttgart	12.2	291	2	48.0	.4	0
Zürich	12.5	284	2	51.3	.2	—1
Basel	13.2	285	2	59.0	(.0)	—2
Hamburg	13.25	312	2	59.4	.5	2
Copenhagen...	13.3	323	3	0.5	.2	—2
Neuchatel	13.6	283	3	5.0	.6	—2
Ksara	13.9	146	3	11.0	.6	1
Pulkovo	14.2	7	3	11.0	.7	—3
Uppsala	15.05	342	3	22.5	.6	—2
De Bilt	15.4	304	3	30.0	.5	1
Uccle	15.6	297	3	33.0	.0	2
Helwan	16.35	166	3	39.8	.7	0
Paris..........	16.6	289	3	43.5	.5	1
Baku	17.8	100	4	1.3	.5	5
Kew	18.6	298	4	8.7	.8	3
Bergen	19.3	329	4	16.3	.5	3
Toledo	23.15	267	4	52.4	.4	—1
Sverdlovsk ...	23.7	50	5	0.5	1.0	
Granada......	24.1	261	5	2.8	.7	

there are only 3 observations. For 16 of the 29 stations the mean deviation did not exceed 0.5. One decimal has been retained in the means although it has no great certainty; it is in order not to introduce greater errors than necessary when differences are formed.

In the Seismicity of the Earth and in the I. S. S. the foci of our 6 earthquakes were not all the same. For a comparison of the travel times with those I calculated a small error in the epicentre would not be serious since most of the stations are in one azimuthal quadrant, the NW quadrant. Nevertheless I tried to adjust the epicentre and since I did not wish to do this by means of a travel time table, I had to use pairs of stations having approximately the same travel times. This restricts us to use only a small number of all the observations available and, for reasons appearing in the course of the work, other objections may be raised against applying the method. However, the result obtained seemed to be an improvement on earlier solutions.

The trial epicentre was that of the I. S. S. for the 1940 earthquakes. When the residuals of the largest shock, that of Nov. 10, were inspected it appeared that the epicentre had been taken too far east. When distances from JEFFREYS' epicentre (see p. 393) were calculated this was found to be too far west.

The pairs of stations chosen are shown in Table 5. az_1 and az_2 are the azimuths of the stations, Δ_1' the I. S. S. epicentral distances of the nearer stations of the pair. δt is the transmission time of the first station minus that of the second station as tabulated in table 4. However, the stations of the last two pairs of stations have been taken as representatives of westerly or northeasterly groups of stations and the transmission times have been so determined as to have the residual that is the mean residual of the group. The $\delta\Delta$ are the differences of distance that according to the travel times I calculated for depth 130 km correspond to the differences of transmission times δt, and the δ are found from :

$$\delta = \cos \Delta_1' - \cos (\Delta_1' + \delta\Delta).$$

Since for small $\delta\Delta$ this difference varies very little with small variations of Δ_1', we may put :

$$\cos \Delta_i - \cos \Delta_k = \delta_i,$$

where Δ_i and Δ_k are the distances from the final epicentre. We have :

$$\cos \Delta_i = \sum a_{i,j}\, a_{0,j}, \quad j = 1, 2, 3,$$

where the a_j stand for the co-ordinates usually called a, b, c and subscript i denotes a station, o the epicentre. We have therefore :

$$\sum a_{0,j}\, (a_{i,j} - a_{k,j}) = \delta_i.$$

Taking all the pairs of stations available we obtain a set of equations from which the co-ordinates $a_{0,j}$ of the epicentre can be obtained. The method of least squares, however, cannot be applied to the equations as they stand for we have $\Sigma a_{0,j}^2 = 1$. We therefore divide by $a_{0,3}$ and obtain :

$$\frac{a_{0.1}}{a_{0.3}}\,(a_{i.1} - a_{k.1}) + \frac{a_{0.2}}{a_{0.3}}\,(a_{i.2} - a_{k.2}) = \frac{\delta_i}{a_{0.3}} - (a_{i.3} - a_{k.3}).$$

TABLE 5

RUMANIAN EARTHQUAKES

PAIRS OF STATIONS

N°	STATIONS	az_1 °	az_2 °	Δ'_1 °	δt sec	$\delta\Delta$ min	δ	Δ_1 ° m	Δ_2 ° m	$d\Delta$ m	$d\Delta'$ °
1	Istanbul-Budapest......	160	291	4.9	−5.9	−27	0.00071	5 11	5 31	−20	−0.3
2	Rome-Potsdam	255	312	11.0	−3.5	−15	84	10 59	11 3	−4	−0.2
3	Chur-Moscow	282	30	12.0	−4.5	−20	123	11 52	12 4	−12	−0.1
4	Ksara-Pulkovo.........	146	7	13.8	0.0	0	0	13 59	14 9	−10	−0.5
5	Helwan-Paris	289	166	16.2	−3.7	−20	164	16 25	16 38	−13	−0.6
6	Baku-Kew	100	298	17.7	−7.4	−39	351	17 51	18 37	−46	−1.1
7	Sverdlovsk-Granada	50	261	23.7	−2.3	−15	176	23 41	24 7	−26	−0.5
8	Georgetown-Zi-ka-wei ..	307	65	71.6	0.0	0	0	71 27	71 26	1	0.2
9	Tokyo-San Juan	50	285	78.9	0.0	0	0	78 57	78 54	3	−0.2

There we have the unknown $a_{0,3}$ on the right hand side of the equation, but since δ_i is small we may substitute $a_{,,3}$ of the trial epicentre for it. Then the equations can be solved for $\frac{a_{0,1}}{a_{0,3}}$ and $\frac{a_{0,2}}{a_{0,3}}$ by the method of least squares and from these quantities the $a_{0,j}$ and λ and φ of the epicentre can be obtained.

The epicentre found from our pairs of stations is 45°50′ N 26°37′ E. It is a little to the northwest of the I. S. S. epicentre taken for most of the shocks. Distances have been calculated from it to all the stations of the pairs ; they are the

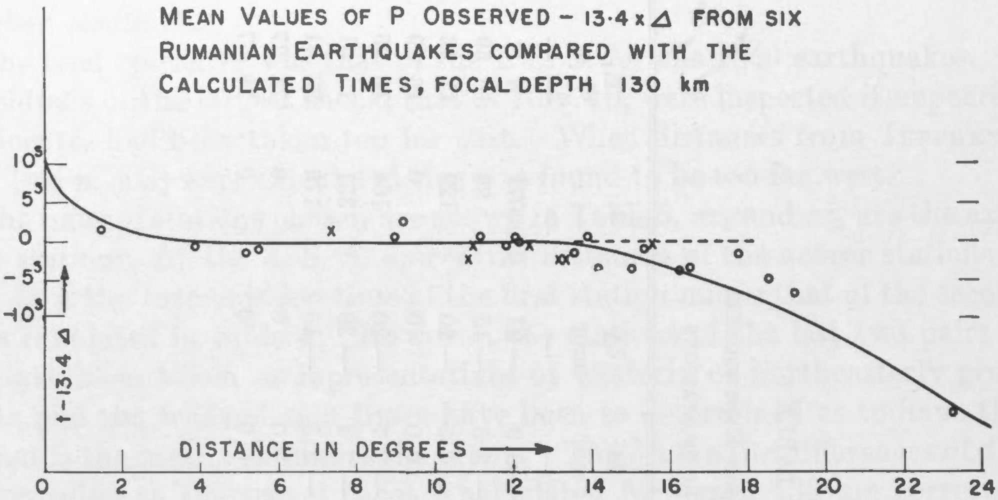

FIG. 2.

Δ_1 and Δ_2 of Table 5. The difference $d\Delta = \Delta_1 - \Delta_2$ should be close to $\delta\Delta$ if we had succeeded in adapting the epicentre to all our pairs of stations. We see, however, that there are considerable differences but that, on the other hand, there is a distinct improvement on the differences $d\Delta'$ of the distances from the trial epicentre.

The epicentre actually taken in the following has latitude 45°49′ N instead of 45°50′. An earlier determination that included an additional pair of stations gave this result, and since the difference is slight, it did not seem necessary to correct the findings based on this value.

The depth was taken to be 130 km. A few trials were made before this depth was fixed on as the one giving the best fit on the velocity assumptions adopted. Obviously it has no great certainty.

It was mentioned in the Rumanian National Report to the I. U. G. G. at Toronto 1957, that the epicentres as determined for the deep Rumanian earthquakes were found to centre on the point 45°.8 N 26°.6 E in good agreement with our present result. A publication by P. IONESCU (1956) was referred to.

The distances of Table 4 are from the epicentre 45°49′ N 26°37′ E, and the residuals are from my trial tables. The inflexion point of the calculated curve is at 10°.1, and the corresponding slope is 13.4 sec/degree. The curve with $(13.4\,\Delta + 5)$ sec subtracted from its ordinates is plotted in figure 2. It is very nearly a straight line from 6° to 13°. The points mark the observed transmission times with $(13.4\,\Delta + 4\,1/2)$ sec subtracted from them. On the whole the fit is not bad, but many of the deviations are larger than would be expected when the accuracy of the observations is considered. The crosses indicate observations, the mean deviations of which do not exceed $0^s.2$. Five of them have residuals of $+2^s$ or -2^s and it is seen immediately from the figure that there is no way of fitting a time-curve closely to all of them.

Taking first the straight part of our time-curve we see that there is no marked systematic deviation from it. Yet when a straight line is fitted to the points at distances from 7°.4 to 12°.5 by the method of least squares, we find its slope to be (13.0 ± 0.2) sec/degree, so the slope is not very well determined. The line of slope 13.0 sec/degree passes through the Warsaw point at 7°.4, but it leaves the points at smaller distances so far below as not to be acceptable. The straight line of figure 2 actually seems to give about as good a fit as is obtainable, and we have to conclude that Warsaw and Rome (10°.9) have systematic errors, Warsaw being about 2^s late and Rome about 2^s early. The slope of our line corresponds to the velocity 8.12 km/sec at the depth of focus.

B. GUTENBERG (1953), when determining the velocity at the depth of focus of three of the shocks here considered, viz. those of 1934, Mar. 29, 1940, Oct. 22 and Nov. 10, found the values 7.8, 8.0, 8.2 km/sec respectively. It is not surprising that the velocities found for individual earthquakes differ so much when no very accurate determination is obtainable from the mean values of the observations of our 6 shocks.

Beyond 13° we have at first a number of negative residuals from well determined travel times. This could be taken to indicate that the actual travel-time curve bends at a smaller epicentral distance and more strongly than our calculated curve, but at a slightly greater distance we have well determined positive residuals indicating a smaller bend, one of them being the Uccle residual, $+2^s$, at 15°.6. The travel-times of Uccle being exactly the same in all 6 shocks its residual is particularly well determined. Thus no travel-time curve can be fitted closely to the points beyond 13°, so here again we have systematic errors. The Swiss stations, Hamburg, Copenhagen, Pulkovo and Uppsala are early while Uccle and De Bilt are late. Baku is very late and probably has a systematic error. Kew and Bergen are also late, but this may partly be due to the time-curve needing a correction.

We had hoped to be able to draw conclusions as to the validity of our velocity assumption by comparing the well determined means of the Rumanian travel times with our calculated curve ; we do not, however, obtain the precise information we were looking for, but instead the somewhat distracting information that the travel-times do not always depend solely on the distance travelled ; they may differ significantly on different paths.

We adjusted the epicentre of the Rumanian shocks using pairs of stations the travel times of which were approximately equal. It is evident that errors are introduced in the epicentre determination when some of the stations have systematic errors and that such errors may affect the result rather seriously when the number of pairs of stations is small.

I shall not venture a guess as to where or at what depth the structures responsible for the differences of travel time are to be found. I shall mention, however, that in an earlier work (LEHMANN, 1949) I tried to determine possible systematic deviations in the travel times of a number of European stations. For this purpose I made use of some Japanese earthquakes very well observed at epicentral distances from about 70° to 80°. No systematic deviations were found for Zurich, Hamburg and Copenhagen (Basel had not been recording). De Bilt was found to be about 1/2 sec late. Uccle and Paris were very nearly normal with a small tendency for Uccle to be early and for Paris to be late. Since in distant earthquakes the rays pass steeply through the upper mantle and the crust, possible differences of structure in them could not make themselves strongly felt. They would be much more effective at distances small enough for the rays to be rather shallow, and have long paths in the upper mantle. In shallow European earthquakes we always come up against various sources of error as already explained, but in the study referred to a few European earthquakes were considered and it was attempted to eliminate the errors. The earthquakes were the two Yugoslavian earthquakes of March 7 and 8, 1931, and the Greek earthquake of 1932, Sept. 26. For these Uccle, De Bilt and Kew were left with positive residuals that no readjustment of the elements of the earthquakes could remove. Their azimuths were 314° and 319° in the Yugoslavian earthquakes, 315° and 320° in the Greek earthquake, but in the Rumanian earthquakes the azimuths were 297° and 307°.

Returning to the Rumanian earthquakes we find that the I. S. S. under the heading « Supp. » has several readings at short intervals after P, and these have been interpreted as either pP or PP. In the large 1940 shocks we have some "pP" readings 6^s to 30^s after P at quite short epicentral distances where the phase could not exist. From 16° onwards the readings become more frequent ; for distances up to 24° most of them have been interpreted as PP. They are from 5^s to 28^s after P. Obviously the readings give us but little information about the behaviour of pP and PP at the distances concerned. It might be possible to trace the two phases if a collective study of the records were made.

We have, as already mentioned, also deep earthquakes in the Tyrrhenian Sea.

The largest occurred on April 13, 1938. CALOI and GIORGI (1951) determined the epicentre 39°.3 N 15°.2 E and found the depth to be 285 km. The travel-time curve for this depth was calculated on my velocity assumptions and compared with observations of reliable stations in the north-westerly quadrant. On the whole the fit is very good, but there are negative residuals of — 3^s at Neuchatel and Basel at about 10° epicentral distance, and the residual + 3^s at De Bilt at 14°.6 ; the Uccle residual is 0^s. A small swing precedes the large P onset in most records, and this may give rise to uncertainties of 1^s — 2^s in the readings, so it cannot be said to what extent the deviations noted are due to differences of structure on the paths.

The inflection point of the calculated curve is at 7°.6 and the slope at this point is 12.25 sec/degree. From 6° to 11° the curve is very nearly straight and has the mean slope 12.2 sec/degree. There are 12 good stations in the northwesterly quadrant in this range of distance ; their residuals are small and have no apparent systematic trend. However, when a straight line is fitted to the travel-time points by the method of least squares, its slope is found to be 12.1 ± 0.4 sec/degree. Thus the uncertainty is considerable and there may be a significant departure from our calculated slope and from the velocity 8.68 km/sec assumed at the depth of focus. The velocity determined by GUTENBERG (1953) is 8.2 km/sec corresponding to slope 12.95 sec/degree.

In conclusion it can be said that our solution for a velocity function is a possible one on the evidence in hand. The travel time curve for a surface focus is in good agreement with JEFFREYS' revised curve for Europe, and the travel times for deep shocks are not in obvious disagreement with the earthquake observations with which we have compared. The solution, however, is not unique. It is possible to find velocity functions differing in various ways from the one here taken, and yet giving travel times that are in good agreement with our data. If, e.g., we alter somewhat the depth of the discontinuity now taken to be at 220 km and at the same time the velocity increase at this discontinuity we may still obtain good agreement with the data. Also, the abrupt velocity increase may be replaced by a strong velocity increase in a thin layer, and we may have a low velocity layer. The calculation of travel-time curves from a given velocity function is a laborious process when an ordinary calculating machine is used. A modern automatic calculator, however, reduces the time required from many hours to a few minutes. It should, therefore, be possible to have travel-time curves calculated on a variety of velocity assumptions and to come to see more clearly what are the limitations placed on them by the data.

It is obvious from the start that the limitations are not so narrow as we could wish them to be. Much more precise data are required for solutions of any accuracy. A great many good observations actually are at hand that have never been reduced with the object of improving the time-distance curve. It is to be hoped that this will be done, but the precision required for a satisfactory determination of the velocity function is so great that it is not very likely to be obtainable in this way. Explosion work may help to improve the results, but it seems possible that increase of accuracy of observation will partly go to reveal variations of travel times on different paths and that mean travel times of very high precision are not obtainable. This is more likely to apply to a continent of so varied a structure as the Eurasiatic continent than e.g. to the Canadian Shield and the Eastern United States.

Our deductions as to the nature of the velocity function are based largely on amplitude observations, but the information obtained from these is rather vague. It would be extremely valuable to have careful studies made with a view to obtaining a clearer picture of the variation of amplitude with distance.

The intense study of surface waves carried out in later years also provides us with means of investigating the structure of the upper mantle. Dispersion curves have been constructed from observations on modern seismographs tuned to respond to very long waves, and the calculation of dispersion curves on given velocity assumptions, formerly a matter of months, can now be done in some hours. This new approach may prove to be of great value.

Note on the focal point of pP

On p. 392 it was mentioned that the time-distance curve of pP is at first retro-

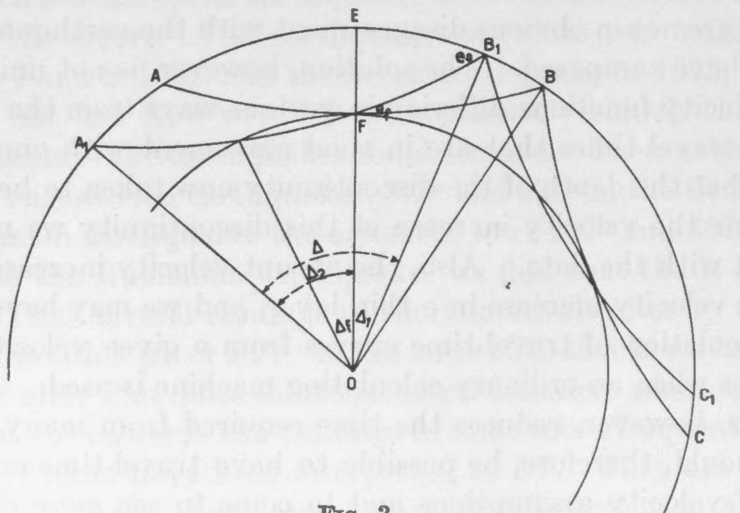

FIG. 3.

grade but turns and becomes progressive at a focal point. This was pointed out by BULLEN (1955), but it may be shown in a somewhat different way.

In the figure the rays leaving the focus F horizontally emerge at A and B. The ray reflected at B emerges at C, FBC being the "first" pP and PP ray. All rays leaving the focus upwards are reflected as pP, whereas those leaving it downwards are reflected as PP. Taking the velocity variation to be « ordinary », with continuous variation of velocity and velocity gradient at the depths concerned, all PP rays will emerge outside C, but pP rays having small angles of emergence at the focus will emerge inside C. Let FB_1 have angle of emergence e_f at the focus and let the complementary ray emerge at A_1. Let the angular distances Δ be as indicated in the figure. B_1C_1 being the ray reflected at B_1, the epicentral distance of C_1 is :

$$EC_1 = 2\Delta_1 + \Delta_2. \tag{1}$$

Under the assumptions made Δ_1 and Δ_2 will vary continuously with e_f and so will their first derivatives. We may write :

$$\frac{dEC_1}{de_f} = 2\,\frac{d\Delta_1}{de_f} + \frac{d\Delta_2}{de_f}.$$

$\frac{d\Delta_1}{de_f}$ and $\frac{d\Delta_2}{de_f}$ have opposite signs but numerically converge towards the same value when $e_f \rightarrow 0$, and therefore $\frac{dEC_1}{de_f}$ has at first the same sign as $\frac{d\Delta_1}{de_f}$. Thus, when B_1 moves from B towards the epicentre, C_1 moves in the same direction, but it does not continue in this direction, for EC_1 is known to approach π when e_f approaches $\frac{\pi}{2}$. There is a minimum distance at which it stops and begins to move the other way. At the turning point we have :

$$\frac{dEC_1}{de_f} = 0.$$

and this is a focal point.

The time-distance curves of pP and PP have their common starting point at epicentral distance EC. The PP curve is progressive, but the first branch of pP is retrograde ; it stops at a focal point where the curve becomes progressive. The common point of the pP and PP curves is a point of inflection ; the constant of the corresponding ray is $\alpha = \frac{r_f}{v_f}$ which is a maximum value.

Taking the velocity function to be given by :

$$v = v_0\left(\frac{r}{r_0}\right)^{-k}, \tag{2}$$

we can find the minimum epicentral distance of pP.

Instead of (1) we can write :

(3) $$EC_1 = \frac{1}{2}(3\Delta - \Delta_f).$$

We have : [(4) p. 384] :

$$\cos\frac{k+1}{2}\Delta = \frac{\alpha}{u_0},$$

and therefore :

(4) $$\Delta = \frac{2}{k+1}e,$$

where e is the angle of emergence at the surface of a ray reaching distance Δ. By (3) and (4) we obtain :

(5) $$EC_1 = \frac{1}{k+1}(3e_0 - e_f),$$

where e_0 is the angle of emergence at B_1. For the pP ray emerging at minimum distance we have :

$$\frac{dEC_1}{de_f} = 0,$$

or :

$$\frac{de_0}{de_f} = \frac{1}{3}.$$

Taking α to be the constant of a ray and $u = \frac{r}{v}$ we have :

(6) $$\alpha = u_0 \cos e_0 = u_f \cos e_f,$$

and therefore

$$\frac{de_0}{de_f} = \frac{u_f \sin e_f}{u_0 \sin u_0} = \frac{\sqrt{u_f^2 - \alpha^2}}{\sqrt{u_0^2 - \alpha^2}} = \frac{1}{3}$$

from which we find :

(7) $$8\alpha^2 = 9u_f^2 - u_0^2,$$

determining the constant α of the pP ray emerging at minimum distance Δ_m. This is the result arrived at by BULLEN written in a different notation.

Using (6) and (7) and introducing into (5) we obtain :

$$(k+1)\,\Delta_m = 3 \arccos\sqrt{\frac{9u_f^2 - u_0^2}{8u_0^2}} - \arccos\sqrt{\frac{9u_f^2 - u_0^2}{8u^2}}.$$

For the time of travel to distance Δ we have [(5) p. 384] :

$$t = u_0 \frac{2}{k+1}\sin\frac{k+1}{2}\Delta,$$

and therefore :

$$(k+1)\,t_m = \sqrt{8(u_0^2 - u_f^2)}.$$

The constant α_f of the ray starting horizontally at F is u_f and we find :

$$8(\alpha_f^2 - \alpha^2) = u_0^2 - u_f^2,$$

u_f differs more from u_0, and therefore α differs more from α_f, the stronger the velocity increase with depth and the deeper the focus. For constant velocity and depth 130 km as taken in the preceding, u_f does not differ much from u_0 ; consequently the first branch of the pP curve is short. We found the "first" point of the pP curve to be at epicentral distance 30°.3 (p. 392) and the focal point is at distance 28°.8.

We have here spoken of pP as propagated in a uniform layer. If there is a discontinuity such as assumed in the preceding, the P part of pP will be refracted when it meets this discontinuity and pP will emerge at a smaller epicentral distance.

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