A geophysical interpretation of structural boundaries in the eastern Canadian shield

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A GEOPHYSICAL INTERPRETATION OF STRUCTURAL BOUNDARIES IN THE EASTERN CANADIAN SHIELD

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SUMMARY

Between 1958 and 1965 field parties of the Dominion Observatory observed some 11,000 gravity stations in northern Quebec as part of a program to provide gravity stations at intervals of 10-15 km throughout Canada. The measurements were carried out using float-equipped fixed wing aircraft and helicopters for transportation.

The gravity measurements have been made by establishing a control network throughout northern Quebec which served as a reference for the gravity traverses. Analysis of the results indicates that the computed Bouguer anomalies in the northern part of the region are accurate to better than 3 mgal and those in the south to better than 2 mgal. The major source of error in the Bouguer anomalies is the uncertainty of the elevations of the gravity stations, most of which have been established using altimeters.

The exposed rocks in northern Quebec are almost entirely of Precambrian age. These rocks have been divided into geological provinces on the basis of structural trends, lithology and K-Ar radiometric age determinations. The oldest of these geological provinces is the Superior province which is Archaean in age. This province underlies the central part of northern Quebec. The younger provinces are distributed around the periphery of the Superior province. The Churchill province, which was last folded in the mid-Proterozoic, lies to the north and east of the Superior province. The Grenville province, which was last folded about 1,000 my ago, lies to the south of the Superior province. The boundaries between the Superior and Churchill provinces

are marked by prominent fold belts consisting mainly of sediments and basic volcanic rocks. The boundary between the Superior and the Grenville provinces is a narrow zone which serves as a transition between the lower grade metamorphic rocks of the Superior province and the higher grade metamorphic rocks of the Grenville province.

Each of the structural boundaries is marked by a prominent linear gravity anomaly. A major feature of the anomalies in each of the areas is a regional negative anomaly with gentle horizontal gradients. In each area there is also a positive anomaly either bordering the regional negative or within it. The horizontal gravity gradients of these positive anomalies require that basic material be present within the crust.

The interpretation of the gravity anomalies is made on the hypothesis that isostatic equilibrium has been maintained during the development of crustal structure. The analysis assumes that in areas where the rocks within the crust are more dense than normal the crust is thicker. This hypothesis is broadly consistent with the results of recent seismic and gravity investigations in Canada. This interpretation excludes the possibility of lateral density variations in the upper mantle, but it is believed that inclusion of sources in the upper mantle would not require that the hypothesis be altered.

Within the Grenville province there are six large local positive anomalies over known anorthositic intrusions. The gravity data indicate that the contacts of these intrusions dip inwards and that, for a positive density contrast of $0.3 \, g/cm^3$ with the surrounding rocks, these intrusions are up to 15 km thick.

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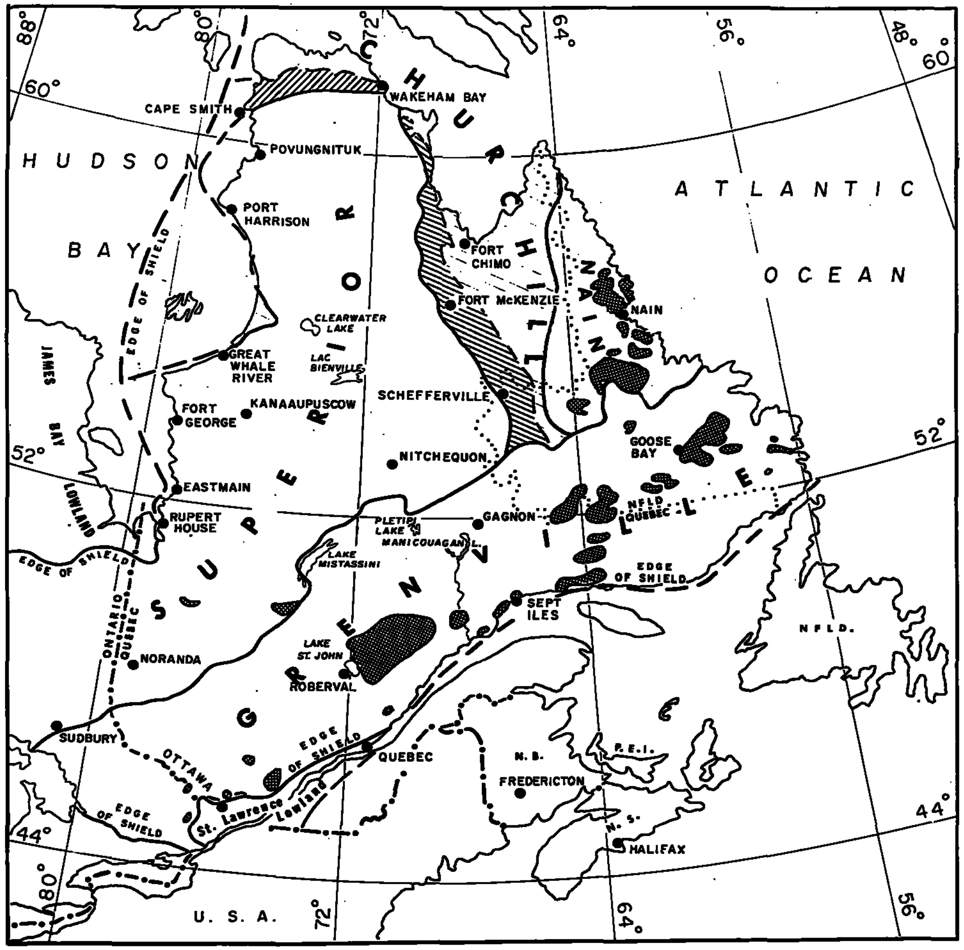
CHAPTER 1

INTRODUCTION

1-1. Introduction

Perhaps the most outstanding discovery of Precambrian geophysical studies in recent years is that of Innes (1957, 1960) who observed large linear Bouguer anomalies in the vicinity of structural boundaries in northern Quebec and Manitoba respectively. These anomalies, which have widths and lengths measured in hundreds of kilometres and amplitudes of tens of milligals, are located over regions where there is an apparent change of regional structural trends (Gill, 1949) and in which there is a marked difference in the average ages of the rocks (Wilson, 1949) on either side of the boundary. Despite this apparent correlation with surface geology it has by no means been established that the cause of these anomalies is at or near the surface. The horizontal gravity gradients suggest that the structures giving rise to the anomalies could in most cases be as deep as 50 km, that is, possibly in the upper mantle or the base of the crust. Since there is very little in the way of other geophysical observations and since geological mapping is, for a variety of reasons, incomplete it is not surprising that different interpretations of these gravity anomalies have been made (Innes, 1957; Innes, 1960; Tanner and McConnell, 1964; Hall and Brisbin, 1965; Gibb, 1968).



LEGEND

GRENVILLE, CHURCHILL, SUPERIOR, NAIN — Structural provinces of the Canadian Shield

Subdivisions in the Churchill Province

- Ungava sub-province
- Cape Smith - Wakeham Bay belt
- Labrador trough

- Anorthosite and related gabbro
- Structural boundary

0 — 500 KILOMETRES

Fig. 1-1

General geography and major geological subdivisions of northern Quebec.

This thesis is a study of the gravitational field in the province of Quebec where there are three such structural boundaries dividing different structural units of the Canadian Shield. To the north in the Ungava Peninsula is the Cape Smith Belt, to the south and extending across the entire map area is the Grenville Front and to the east is the Labrador Trough. These boundaries separate the apparent oldest geological province from the younger, surrounding provinces.

The remainder of this chapter will be devoted to factors pertinent to this geophysical study of northern Quebec. As such this will consist of a general description of the geography, the gravity work and a statement of the aims of this investigation. The geology of the area will not be discussed here, but rather in Chapter 4. For the moment it is sufficient to be aware that northern Quebec is underlain almost entirely by Precambrian rocks divided into the structural provinces as shown in Fig. 1-1.

1-2. General Geography

The term "northern Quebec" as used here refers to that part of the Province of Quebec lying north of about 49°N. The total area of the region is about a million square kilometres. In the subsequent remarks on the geography of northern Quebec a description of the topography will not be included because it is more convenient to consider the details of the topography as they are required. Like most Precambrian areas, northern Quebec can be considered broadly as a peneplain with an average elevation of about 300 m. With the exception of the Grenville geological province the relief is generally small.

Insofar as gravity surveys are concerned, the dominant geographic factors of northern Quebec are its remoteness and its climate. These factors are important to the point that their influence on the performance of the instruments had to be carefully documented. In general, these factors are not conducive to straight forward surveys and require that planning allow for as many contingencies as possible.

By far the greatest part of northern Quebec is tree-covered, often densely. This tree cover extends northward to a line joining Hudson Bay at about 57°N, Fort Chimo and Nain on the coast of Labrador. North of this line is largely moss and grass-covered. The trees are mainly coniferous although large stands of deciduous trees, usually poplar, do occur. In the south the coniferous tree cover supports extensive logging operations.

The extensive tree cover befits the climate which is hospitable to little but the development of forest cover. On the average the mean annual temperature is only slightly above freezing and in the summer months the average temperature is about 45°F. The water cover remains frozen until mid-May in the south and late June or early July in the north. The ice cover commences to reform in October in the north and late November in the south. The total annual range in temperature is large, usually 100°F or more for all parts of northern Quebec. The average rainfall varies from about 10 m in the south to about 0.3 m in barren lands to the north. The cloud cover is usually extensive throughout northern Quebec, even in the far north where the annual precipitation is relatively low. Cloud cover, often solid and low-lying, is present about 75% of the time in the summer months.

The key to access to northern Quebec is the vast system of lakes and rivers which enable travel by float-equipped aircraft to all parts of the area. Basically, there are three main drainage systems; one which drains to the west into Hudson and James Bays, one to the south into the Gulf of St. Lawrence and the St. Lawrence River, and one to the north into Hudson Strait and Ungava Bay. By far the largest of these is the Hudson and James Bay system which approximately coincides with the Superior geological province as shown in Fig. 1-1. Lakes are abundant and the rivers meander considerably due to the flatness of the terrain within the basin. Hudson Strait and Ungava Bay serve as catch basins for the area north of the Cape Smith Belt and the Labrador Trough. Lakes are numerous and the rivers more direct. In the Labrador Trough the river basins are controlled by structural trends and north of the Cape Smith Belt by the presence of steeply walled valleys which developed in response to rapid uplift upon deglaciation. The St. Lawrence drainage system comprises largely the Grenville geological province. Lakes are abundant and the rivers are commonly located in deep steeply walled valleys and feature numerous rapids and falls, many of which are spectacular and not typical of those found in Precambrian terrains generally.

The population is distributed around the periphery of northern Quebec. Communities in the north receive the bulk of their supplies by boat in summer, but there is often a weekly scheduled visit by aircraft to bring mail and a limited amount of current supplies. The Labrador Trough area is serviced by a railroad connecting Schefferville to Sept Iles on the Gulf of St. Lawrence. This railroad is used mainly for transporting iron ore. The extreme southern part of northern Quebec is on the fringe of the populated region and is served by rail, road and air traffic.

The main means of communication in northern Quebec is the radio. Radio and weather stations are distributed at roughly 500 km intervals throughout the region and all northern communities also have transmitting equipment, usually operating by the manager of the local Hudson's Bay Company establishment. Transient field parties in the area are well supported by the operators of these communication facilities and the assistance rendered in both normal situations and emergencies has been a prime factor in the success of many field operations.

1-3. Summary of Field Operations

The first gravity surveys in Northern Quebec (Innes, 1957; Thompson, and Garland, 1957) were made in the early 1950's. These operations were carried out using float-equipped, single-engined Norseman and Beaver aircraft. These surveys were reconnaissance in nature with gravity observations spaced at approximately 30 km intervals. In the late 1950's it became obvious, because of factors such as rate of progress, station distribution and safety of operation, that an operation employing a single aircraft was not satisfactory and in 1958 the program reported here was initiated. The program was revised to allow for the use of at least two fixed-wing aircraft, stations at 10-15 km intervals and greater areal coverage annually. In the early years of the program Beaver aircraft were used for both the measurements and moving camp and a Canso aircraft was used to establish gas caches for the Beaver aircraft.

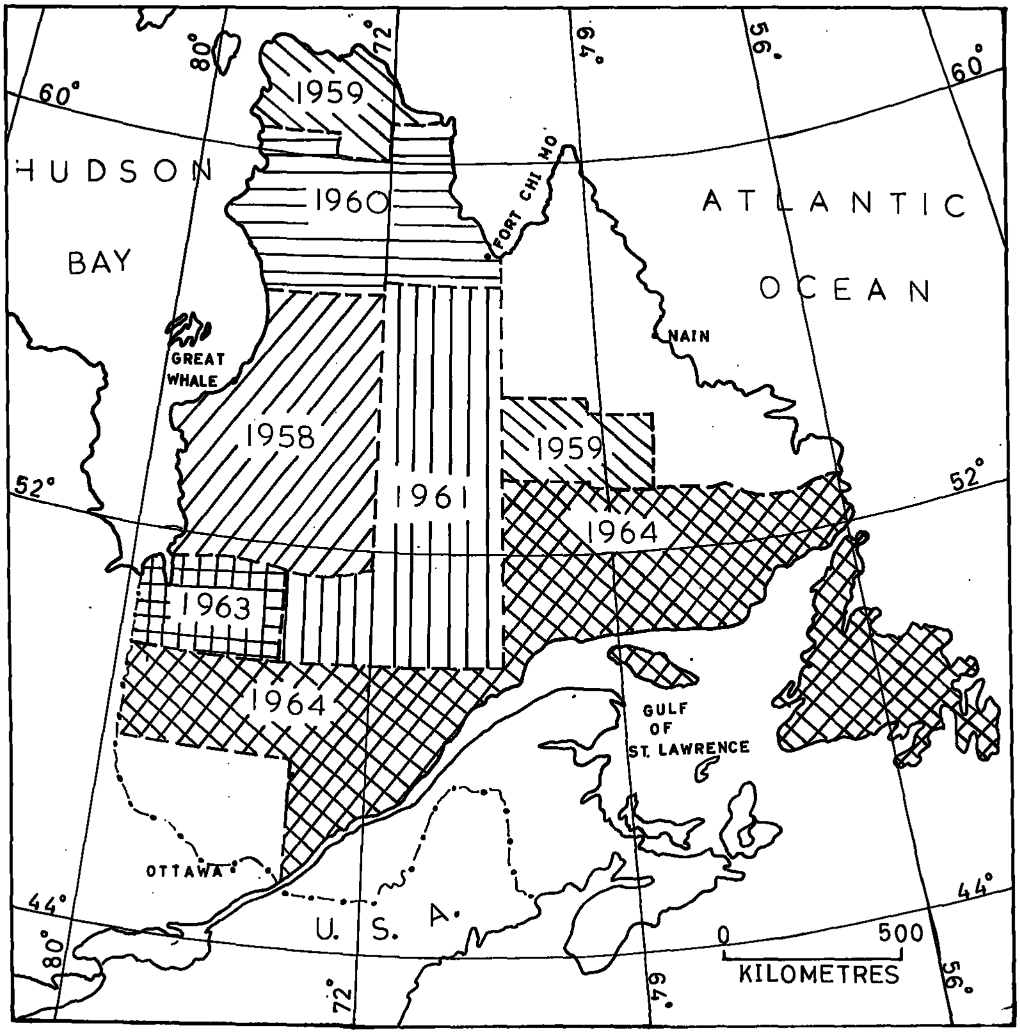


Fig. 1-2
Distribution of gravity surveys in northern Quebec since 1958.

In the early 1960's it was decided to switch to helicopters for the gravity operations because of economy and because the Beaver aircraft had access to only the lowest lying areas. The use of helicopters permitted gravity observations to be made over the entire range of elevation, which provides a set of data more useful for future isostatic studies. This type of operation in which two helicopters, a Beaver (general support) and a Canso (to move camp) provide transportation has proved efficient and is still used by the large field parties of the Observatory.

The field parties carried a full complement of camping gear including radio transmitters. In each year but 1964 it was customary to establish several main camps from which an area about 20,000 km^2 could be covered. The areas covered by the field parties are shown in Fig. 1-2.

1-4. Aims of this Investigation

The first, and the most important contribution to be made is a set of good observations whose reliability is reasonably well understood. Interpretations can be invalidated quickly by subsequent work, but good observations will remain useful to earth scientists for a considerable time after the completion of the particular project. The procedure followed in the field operations was designed to provide the best possible data under the existing conditions. A description of these procedures and the methods used to reduce the data are described in Chapter 2. Also contained in this chapter are the results of systematic efforts to determine the accuracy of the data.

The limited information usually available for any area has necessitated the development of a method of interpretation that can provide a convenient test of different assumptions so that possible limits can be placed on the model. In Chapter 3 an automated method of interpretation is presented. This is a reproduction of a paper published by the author (Tanner, 1967).

The remainder of the paper is devoted to correlation of the gravity data with geology and topography and to the interpretation of the observed gravity anomalies. The major emphasis in this interpretation will, of course, be placed on the anomalies in the vicinity of the boundaries between the geological provinces. Since this will involve an analysis of gravity anomalies over areas whose dimensions are hundreds of kilometres by hundreds of kilometres, efforts will be made to consider the interpretation in the context of the total geological and geophysical situation and not simply that at the boundary. Local interpretations will be made of several anorthosite and basic intrusions in the Grenville subprovince. Although the term "local" is used, it is emphasized that these features have horizontal dimensions measured in tens of kilometres.

At the conclusion of each chapter of the interpretation, discussion of the results will be given. The last chapter contains the main conclusions of this study.

CHAPTER 2

THE MEASUREMENTS AND THEIR REDUCTION

2-1. Introduction

2-1-1. Principles of surveys.

The basic approach to the measurement and reduction of the gravity data obtained during surveys in northern Quebec has been one of maintaining uniformity and simplicity of procedures. The surveys, which were planned to provide gravity observations at 10-15 km intervals throughout areas as large as 5×10^5 km^2, took place mainly in areas accessible only by aircraft and involved extensive logistics. The achievement of the objective of the surveys simultaneously with the safe and economical operation of the aircraft required that the field programs be well organized prior to departure for the field and that the gross plan of the operation be followed strictly. Some provision was made to provide more detailed gravity data in areas of unusual anomalies, but detailed investigations, however interesting, were given second priority to completion of the regional coverage.

Although these surveys were intended primarily to provide regional gravity data for investigation of regional crustal and geological structure, they were also intended for use in geodetic and isostatic studies and to serve as a basis for future investigations either by the Observatory or by some other research and/or mineral exploration organization. It was therefore important that systematic errors in the measurements be reduced to a minimum and that the precision of these measurements, both overall and in detail, be estimated as accurately as possible.

The above requirements have led, since the inception of the program in 1958, to the gradual development of groups which specialize in the establishment of control station networks and calibration standards, the planning and execution of the regional surveys, and the reduction of the field data and the preparation of the gravity anomaly maps. These three functional groups carry out independently research in their own areas of responsibility to improve or develop methods and procedures and collectively apply the results of there investigations to the overall program of regional measurements.

TABLE 2-1

SUMMARY OF NORTHERN QUEBEC GRAVITY SURVEYS

Year	Observer	Instrument	Stations
1956	J.G. Tanner	N.A. 137	47
1958	D. Lepard	W 422	430
	R.K. McConnell	W 433	510
1959	R.J. Buck	W 433	272
	R.K. McConnell	W 391	201
	D. Lepard	W 444	398
1960	H. Davidson	W 391	606
	B. Van Oort	W 431	422
1961	R. Reader	W 391	816
	D.F. Weaver	W 433	848
1963	J.P. Charette	W 431	40
1964	M.R. Dence	W 546	90
1964	J. Weaver	W 391	1387
	J. de Kort	W 431	1109
	P. Richard	W 433	795
1965	J.G. Tanner	G-7	93
	J.B. Boyd	W 546	38

Table 2-1 provides a summary of the surveys carried out in Quebec. The field work listed in 1965 involved special traverses across the Grenville Front, the Cape Smith Belt and some of the basic intrusions in the Grenville geological province. In addition to the extra gravity stations observed, a large number of rock samples were collected while on these traverses.

2-1-2. General Procedures.

The instruments used by each observer included a gravimeter, two altimeters and a sling psychrometer. The gravimeter and the altimeters were read at each gravity station. The wet and dry bulb temperatures were recorded at every second or third station unless the elevation changes between successive stations were large in which case they were read at each station. The location of the station was marked carefully on a topographic map at a scale of either 1:250,000 or 1:500,000. Finally, if an outcrop was available, a rock sample(s) was taken for a density determination.

The care and protection of the instruments in transit required constant attention to reduce the effects of shock due to turbulence and to rough water during landing and take-off of the aircraft. During the survey in 1959 specially constructed protective cases mounted to the floor of the aircraft were tried. These cases were well padded and did afford the instruments protection while in transit, but they were rather bulky and in the close confines of the aircraft it was difficult for the observers to avoid bumping the instruments when handling them at the station. Subsequently the cases were discarded and the instruments placed in the rear of the aircraft well padded with sleeping bags.

At the stations it was usually necessary to wade ashore from the aircraft and to walk over boulders and other debris to a spot suitable for reading the instruments. The treacherous footing sometimes resulted in minor mishaps (bumps, etc.) which caused the gravimeters to jump by several tenths of a milligal. The only solution to this problem was care when handling the instruments and frequent testing to ensure the instruments were not damaged.

Both in transit and on the ground the instruments were continually exposed to dust, sand and moisture and required cleaning, adjusting and testing regularly.

2-2. The Gravity Measurements

2-2-1. Instrumentation.

All the gravity measurements reported here were made with either the Worden or the LaCoste-Romberg gravimeters; the latter were used to establish control stations only during the field seasons of 1963 and 1964. The quartz-fabricated Worden instruments used have scale constants of about 0.4 mgal/div and ranges of 300 to 800 mgal without resetting. These instruments have a built-in temperature compensation unit and some of them, the Master models, are equipped with a heating unit to control their internal temperature. Some Master models were used on the surveys, but not on heat. In the absence of temperature control Worden instruments are temperature sensitive. For example, Innes (1960) demonstrates that these instruments will respond almost immediately to sudden changes in external temperature, that the reading increases with increasing temperature and that the rate of change of reading is proportional to the rate

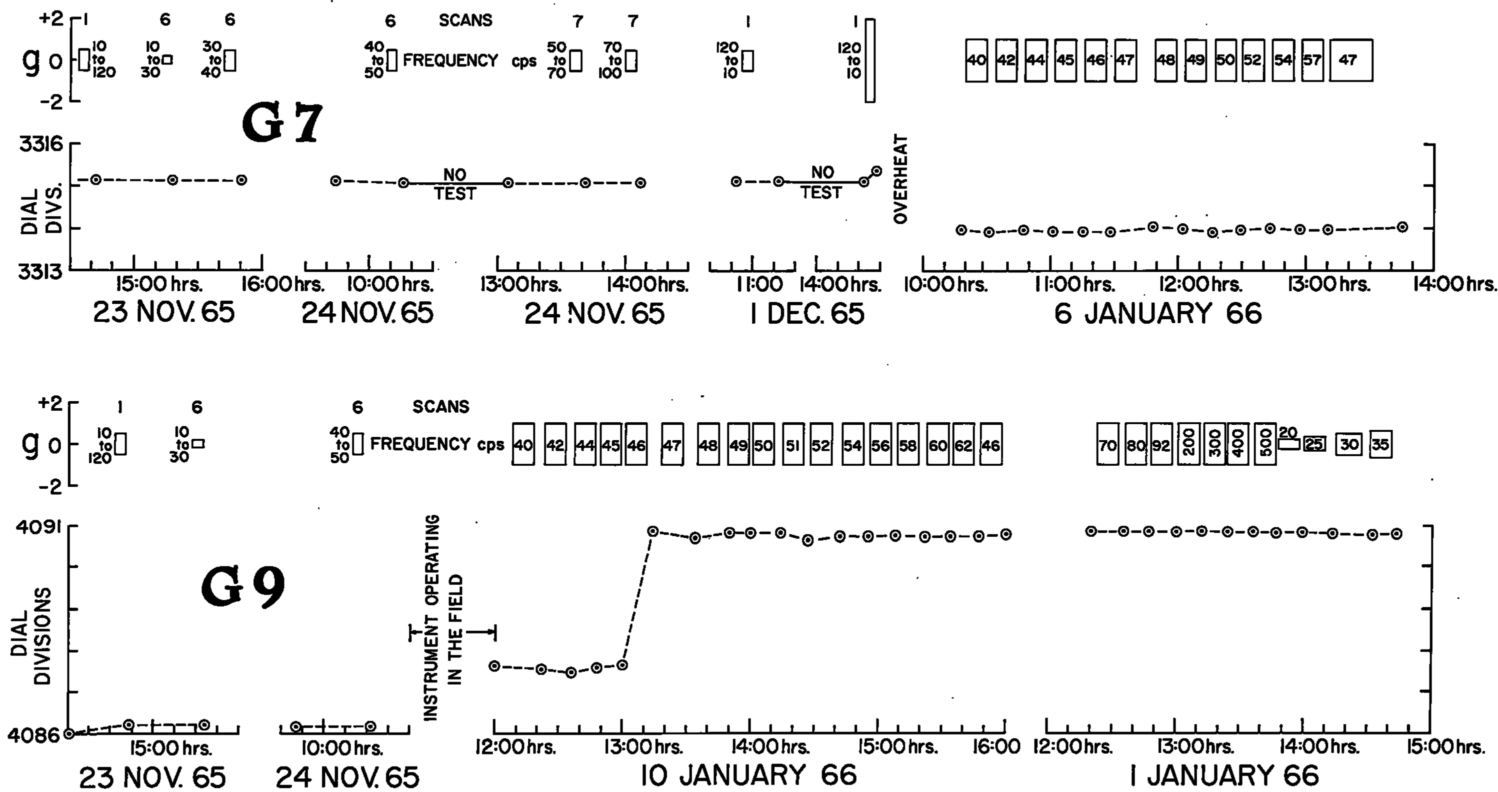


Fig. 2-1

Summary of tests of effects of vibration on LaCoste and Romberg gravimeters g7 and g9. Note the generally flat character of the reading curves.

of change of temperature. A.C. Hamilton (personal communication) has shown that the scale constant of the Worden gravimeter changes linearly with internal temperature and has determined the correction necessary if the internal temperature at the time is known. Provision for this correction has been made in the computer programs used to reduce the observations. As far as is known these instruments are not particularly sensitive to vibrations but shock may result in a change of zero reading of the instrument.

The LaCoste-Romberg gravimeter, which has a world-wide range without resetting, is constructed of metallic components and must be thermally controlled. This instrument is practically drift free and is probably by far the best gravimeter available commercially. However, recent tests of the Observatory's LaCoste-Romberg gravimeters on a vibration table (Hamilton and Brulé, 1967) have demonstrated that when subjected to vibrations in the range 40-50 c/s under accelerations up to ±2g, these instruments can behave erratically. Fig. 2-1, reproduced from Hamilton and Brulé's paper, shows that vibrations can result in substantial changes of reading; in this case about 4 mgal in 10 min. The authors conclude that, since vibrations and accelerations in the ranges stated above can occur in aircraft, their tests provide and explanation of erratic drift by the LaCoste-Romberg gravimeters. Hamilton and Brule also found that this vibration induced drift could be largely eliminated by the use of mechanical isolators in the carrying case. It is unfortunate that this research was documented too late for application in Quebec. However, according to the tests by Hamilton and Brulé, large jumps are not common; jumps of 0.1 - 0.3 mgal would seem more usual.

2-2-2. Calibration of the Gravimeters.

Since the total range of gravity in Quebec is about 1500 mgal and since the range of gravity experienced in any one survey could be as large as 500 mgal, adequate calibration of the gravimeters is important not only to avoid large systematic errors in the measurements, but also to ensure that the same standard of measuring gravity is maintained from year to year. Since the Observatory's pendulum apparatus was undergoing reconstruction during the years of the surveys, it was necessary to use the Ottawa-Washington calibration line (Innes, 1958) as the standard of gravity measurement.

This line, which covers a range of gravity of about 500 mgal, is based on pendulum measurements by the Observatory's bronze pendulum apparatus and the Gulf quartz pendulum apparatus. If all measurements by both sets of pendulums be accepted as equally valid, then a comparison of these measurements indicates that this gravity interval is uncertain to about ±0.5 mgal and that the scale constants may be systematically in error by about one part in one thousand. On this basis a systematic error of 1.5 mgal could be expected over the total range of gravity in northern Quebec.

In addition to the calibration line the Observatory's tilt table has been used to calibrate the Worden gravimeters subsequently to 1961. Although this particular program was intended to study the linearity of the dial of the Worden gravimeters, the results of the tilt table measurements were compared to the results obtained from the calibration line. Initially the disagreement between these two independent methods of calibration was fairly large because the

TABLE 2-2

ADOPTED SCALE CONSTANTS FOR GRAVIMETERS USED

IN NORTHERN QUEBEC *

INST	YR	1958	1959	1960	1961	1962	1963	1964	1965
L&R #7		-	-	-	0.99928	-	0.99935	0.99916	0.99932
L&R #9		-	-	-	0.9996	-	0.99967	0.99976	1.00027
L&R #74		-	-	-	-	-	-	0.99951	0.99951
W #391		-	0.40459	0.39917	0.39899	-	-	-	-
W #422		0.54181	-	-	-	-	-	-	-
W #431		-	-	0.39931	-	-	-	-	-
W #443		0.39785	0.39748	-	0.39825	-	-	-	-
W #444		-	0.49563	-	-	-	-	-	-
W #460		-	-	-	-	-	-	0.45152	-
W #546		-	-	-	-	-	-	0.39886	0.39865

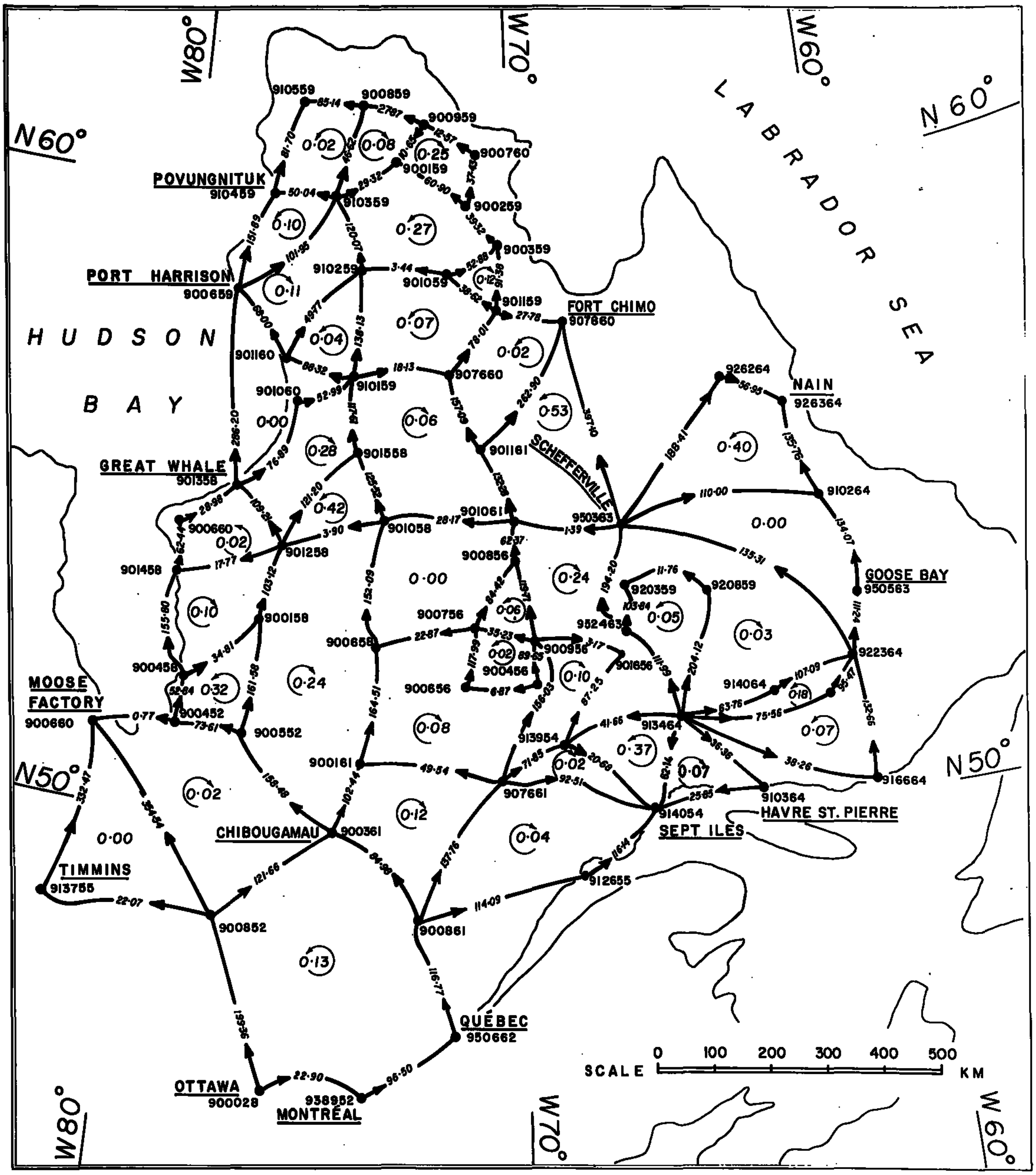
*Units = mgal/scale division

dimensions of the tilt table were not known to sufficient accuracy. The dimensions of the tilt table were subsequently determined more accurately at the National Research Council of Canada and thereafter the two methods agreed to about one part in twelve hundred.

The adopted scale constant for each instrument by years, based on one to three calibrations yearly, is given in Table 2-2 and with few exceptions there is little change in the instruments' constants from year to year. One exception is that for Worden #391 which between 1959 and 1960 changed by about one part in a hundred. This particular instrument was involved in a plane crash in 1959 and was returned subsequently to the factory for repairs.

2-2-3. The Control Network.

The control network (Fig. 2-2) was observed mainly in conjunction with the regional mapping program, although additional long range connections not shown on the diagram have been made as part of a program to establish a fundamental gravity network for Canada. Control stations are, on the average, spaced at 125 km intervals throughout northern Quebec; a spacing chosen to permit direct ties between adjacent control stations to be made within one hour. All the connections in the years 1958-61 were made with Worden gravimeters and the remainder, including long-range connections, were made with the LaCoste-Romberg gravimeters. The base lopping procedure (Nettleton, 1940) was always used with the Worden gravimeters and mean differences of reading obtained by preparing drift curves on the assumption that the drift rate was linear. Since the LaCoste-Romberg gravimeters are practically drift-free, the base looping



52·99 → GRAVITY DIFFERENCE IN MILLIGALS. ARROW INDICATES DIRECTION OF INCREASING GRAVITY.

0·11 CLOSURE ERROR IN MILLIGALS. ARROW INDICATES DIRECTION IN WHICH GREATEST GRAVITY DIFFERENCE IS OBTAINED.

901060 - CONTROL STATION NUMBER

Fig. 2-2

The basic gravity control network of northern Quebec. In addition to the connections shown, long and medium range ties not shown, have also been made.

procedure was not used with these instruments. Acceptable results can be obtained with these instruments using differences in reading corrected for earth tides provided the structure of the network is strong as a result of numerous repeated connections and as many interconnections between control stations as possible. This condition was realized in 1963 and 1964, since the Beaver aircraft was employed exclusively for support of the helicopters and, in this role, was required to cover large areas daily which permitted numerous connections between control stations to be made.

2-2-4. The Regional Measurements.

All the regional gravity stations were established by traversing between control stations with Worden gravimeters. During each traverse single readings of the gravimeters were taken at each site, including the control station readings at the beginning and the end of each traverse. Whenever possible the gravimeters were read at least three times daily at a control station - one usually in the early afternoon because of the characteristic reversal of direction of drift in response to the usual daily decrease in temperature towards evening - to minimize the error due to the assumption of linear drift in reducing the observations.

In good weather it was possible for one observer to make as many as thirty five observations during a day. However, the average number of observations per observer per day throughout all the surveys was twenty or less, largely because of the rather poor flying conditions which prevail throughout most of northern Quebec. Another factor which influenced the daily production was rock sampling. Proper sampling added five minutes or more to the time on the ground at each station and during periods when few days were suitable for flying there was a tendency to forego rock sampling and obtain a higher production of gravity measurements. Attempts were made at various times to reduce the areal coverage to permit more rock sampling but, because of the weather, the problem of choosing between rock sampling and the gravity observations was to some degree encountered during every survey. Rock sampling will be discussed in a later section of this Chapter.

2-3. Elevation Measurements

At this stage in the development of northern Quebec its relative inaccessibility precludes the possibility of an extensive network of both precise level and transit lines. Consequently the only elevation data available for reference were hilltop elevations established by transit, lake level elevations established by both radar and aneroid altimeter surveys of the Topographical Survey of Canada, and, on the borders of the region, mean sea level. Unfortunately these elevations were not sufficiently numerous to provide an elevation for every gravity station and it was necessary to supplement these data with further altimeter work.

All the altimeter measurements in Quebec were made using aneroid type barometers, calibrated in feet, manufactured by Wallace and Tiernan. The particular models purchased by the Observatory cover a range of elevation from mean sea level to either 4000 or 7000 ft and are read directly from a circular scale calibrated at intervals of 5 ft. The face of the altimeter contains an annular mirror to avoid parallax when determining the position of the pointer with respect to the scale. The manufacturer claims these instruments to be insensitive to changes of temperature. Tests of the instruments used on the surveys, carried out at the National Research Council of Canada, support this claim.

For practical reasons it was decided to traverse the altimeters with the gravimeters and to use the reference elevations rather than base altimeters as the basis for determining changes of atmospheric pressure. Base altimeters were considered, but were not used because they are effective for a range of about 40 km only and because their use requires a coherent (and accurate) network of reference elevations for the recording sites.

The distribution of the reference elevations varied considerably throughout northern Quebec. In the southerly regions it was possible to arrange the gravity traverses such that a reference elevation was available for every third station, which meant that a determination of the variation of atmospheric pressure could be obtained roughly every hour. In the north, particularly in the area surveyed in 1959, the reference elevations are more thinly distributed and on occasion the interval between readings at successive reference elevations was as much as 8 hr. Generally, however, it was possible to tie into reference elevations in the north every 3 or 4 hr. Since some reference elevations in Quebec could contain errors of about the same magnitude as those usually present in altimeter measurements, it was necessary to make detailed comparisons of data from different sources. The process of determining the elevations of the stations, which occupied considerable time both in the office and in the field, can be summarized as follows:

(a) prior to the survey record all known elevations, source of information and estimated accuracy,

(b) take as many repeated altimeter readings as possible, including frequent observations at mean sea level,

(c) carry out preliminary reductions of the data in the field and re-observe any apparently erratic results, and

(d) adopt elevations for all reference stations and carry out the final reduction of the altimeter data by computer after the completion of the survey.

The elevations of the reference stations for which more than one elevation value was given were usually obtained by averaging, but knowledge of the drainage patterns, the Bouguer anomalies themselves, and the fact that most of northern Quebec is relatively flat-lying all proved useful at one time or another as a basis for rejecting elevations.

2-4. The Density Measurements

The determination of rock density was the least successful of all phases of the work since suitable sampling could be achieved only in connection with local surveys when the requirement for areal coverage was not pressing. Another major factor contributing to the incompleteness of the results was the lack of accessible outcrops. In many cases outcrops could be seen along the shores of lakes, but could not be approached with aircraft because of wind conditions, rocks and boulders, or overhanging trees and undergrowth. In other areas, some of which were large, there were very few outcrops and rock samples were consequently difficult to obtain. A more general problem often arose because some of the observers on the field parties were student physicists who had received little or no training in geology, and therefore, tended to gather samples which were neither representative of the rocks of the area nor fresh and of little use for density measurements. On the job training by those on the party with a background in geology helped to alleviate this situation.

The density of the rocks were determined in the usual way. The weight of the samples, in air and in water, were determined with a balance, which bears the distinguished name "EÖTVÖS", accurate to 1 g. As has been shown by Tanner and Uffen (1960), the density of most rock samples weighing 350 g or more can be calculated accurately to 0.01 g/cm^3 when the weights in air and water are known to the nearest gram. All the samples were weighed in their natural state and no attempt was made to determine either the saturated or unsaturated density because the rocks were all crystalline, and not porous and, therefore, very little difference in the dry and saturated densities would be expected (Heiland, 1946, p 76, Tables 10, 11).

The rock samples were usually identified by a geologist familiar with Precambrian rocks. The description of the sample, which was intended for use on a punched card system, consisted of a name (gneiss, gabbro, etc.) followed by up to four modifiers listing such things as the most prominent minerals, the grain size, the colour, the structure and other relevant descriptive terms.

2-5. Reduction of Data

2-5-1. The Control Network.

The gravity values adopted for the control stations shown in Fig. 2-2 are based on an adjustment made in 1960 using a relaxation method (Smith, 1951; Bancroft, 1960) and are relative to a value of 980.622 gal for the National Reference Station in Ottawa (Miller, 1931). At the time of the adjustment the control network consisted of a relatively loose frame-work of Worden and North American loops. Control stations established subsequently to this adjustment were assigned gravity values, either by linear interpolation or by a local least squares adjustment, consistent with those given by the 1960 adjustment.

Recently the author carried out a formal least squares adjustment of the Quebec network using a slightly modified version of Cook's (1954) method. This adjustment was carried out mainly as a preliminary to incorporating this network into the national network. However, the results of the adjustment are of interest here for comparison with the "mapping values" used to reduce the regional observations.

Cook's method provides for the adjustment of the scale constants of the instruments by the inclusion of pendulum measurements to set the scale of the adjustment. In the absence of sufficiently precise pendulum measurements in Quebec, the scale of the adjustment was set by assuming the interval Ottawa-Fort Chimo (1108 mgal approximately) to be fixed. Other details of the adjustment are as follows:

(a) 345 LaCoste connections, 95 Worden connections and 5 North American connections were included in the adjustment,

TABLE 2-3

SUMMARY OF

COMPARISON OF 1960 AND 1967 ADJUSTMENTS

Mean of differences with regard to sign (mgal)	0.01
Mean of differences without regard to sign (mgal)	0.10
R.M.S. adjustment (mgal)	±0.13

TABLE 2-4

SUMMARY OF

COMPARISON OF ADOPTED AND ADJUSTED SCALE CONSTANTS

Mean of differences with regard to sign (ppt)*	-0.5
Mean of differences without regard to sign (ppt)	0.7
R.M.S. difference from mean (ppt)	±0.7

*parts per thousand

(b) in accordance with the results of an analysis of the performance of all instruments on the Ottawa-Washington calibration line (A.C. Hamilton, personal communication) a LaCoste tie was assigned a weight of 1.0 and a Worden or North American tie a weight of 0.6,

(c) no reduction of weight was made for connections between primaries via an intermediate control-station, but one North American connection obtained by adding five loops together was given a reduced weight of 0.3,

(d) the number of control stations (excluding Ottawa) was 75 and the number of instruments (instrument years) 20.

Trial values were assigned to each unknown in the solution (Garland and Tanner, 1957) and the computer program (Appendix 3) calculated the adjustments to these trial values.

The standard deviation of an observation of unit weight is calculated to be ±0.07 mgal. The standard deviations of the adjustments to the trial gravity values vary from about ±0.01 mgal to about ±0.10 mgal. A summary of the comparison of the adjusted values of gravity with the "mapping values" adopted on the basis of the 1960 adjustment is given in Table 2-3. The adjustments are all less than 0.25 mgal in magnitude and do not seriously affect this work.

A summary of the adjustments to the scale constants is given in Table 2-4. The fairly large standard deviation from the average adjustment is due to the unusually large adjustment of 2.5 parts per thousand (hereafter ppt) to the trial scale factor adopted for North American #137 in 1956. This instrument was not calibrated on the same basis used in 1958 and subsequently.

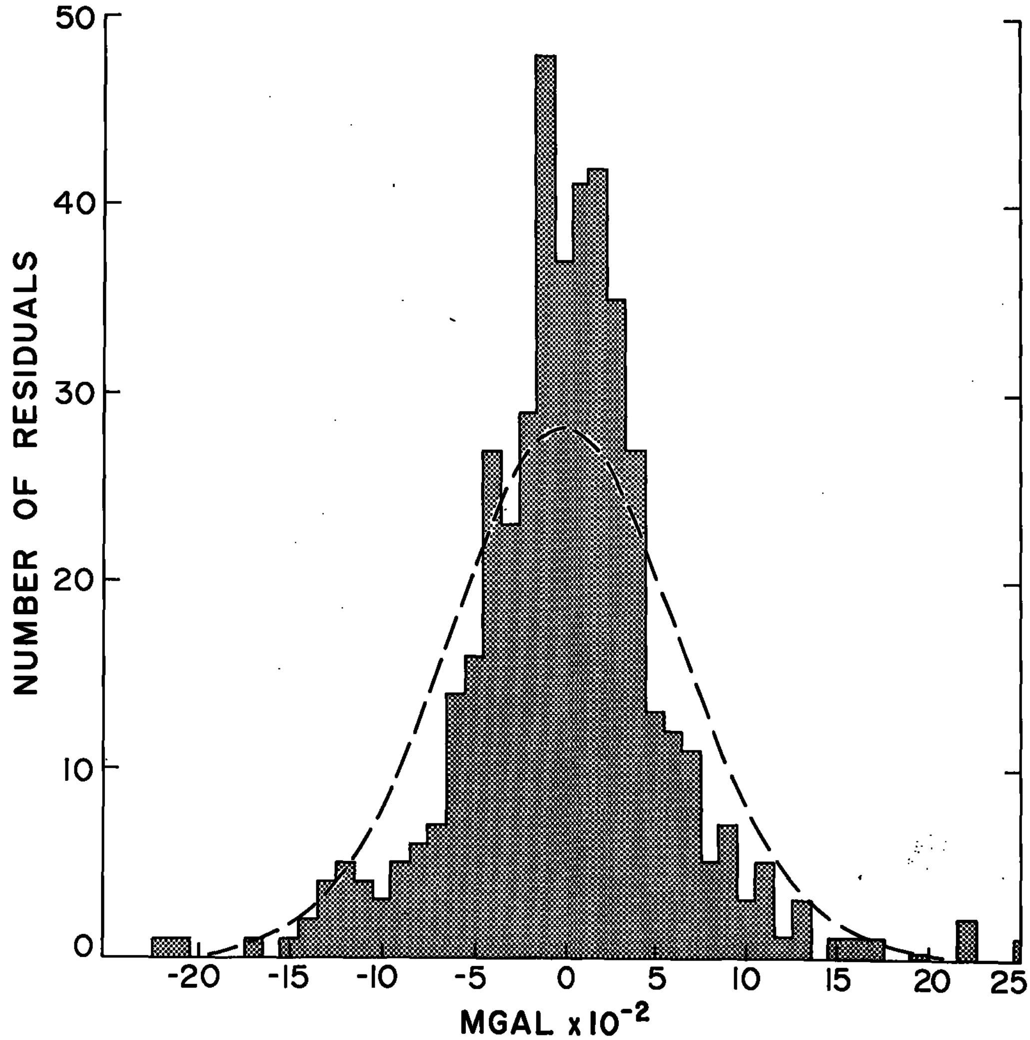


Fig. 2-3

Distribution of residuals after adjustment of northern Quebec control network.

Fig. 2-3 shows that the distribution of the residuals, compared to the normal curve for the same standard deviation, has a surplus of small residuals; and a deficiency of medium sized residuals. There would appear to be at least three possible explanations for this:

(a) errors due to rounding and truncation in the computations,

(b) a normal distribution is not necessarily expected, and

(c) jumps in the gravimeter readings.

The first of these has been tested by computing the residual matrix

$$\underline{R} = \underline{N}^{-1}\underline{N} - \underline{I}$$, where $\underline{N}$ is the normal matrix,

from which the quantity

$$m = \max_i \sum_j |R_{ij}|$$

was calculated. In this case m equals 0.005 which suggests that the solution is valid to two significant figures and that the histogram in Fig. 2-3 does not reflect rounding errors in the calculations.

Much has been written on the second point by a number of authors. Sunter (1965) has pointed out that, in networks consisting of repeated measurements of each interval in the network, the variance of each interval is not necessarily the same and that a normal distribution of residuals might not be expected. In principle, the weights of the observations should take this into account, but in practice optimum weighting is difficult to achieve, particularly when a variety of instruments and observers are used to establish a given network, as is the case for the Quebec network. This factor cannot be excluded.

The last possibility cited above would appear most relevant to the situation in Quebec. Cook (1951) has shown that, if there are random jumps in the reading of the gravimeter at intervals of time T, then a distribution with properties similar to that shown in Fig. 2-3 can result. It will be recalled that there is good reason to expect that both the Wordens and the LaCostes were susceptible to jumps, and if it is assumed that these occurred approximately at regular intervals then Cook's explanation could account for the departure from a normal distribution.

2-5-2. Computation of the Bouguer Anomalies.

Since 95% of the measurements made in northern Quebec were regional observations, this section is primarily concerned with the procedures followed to calculate the Bouguer anomalies for these observations. Bouguer anomalies have been calculated for the control stations, usually separately, by the same procedure used for the regional observations once the observed gravity was calculated.

The reduction of the data observed on a field survey began in the field and continued in the office at the completion of the survey. In the field the reductions were carried out by hand using forms from which punched cards could subsequently be prepared. The field reductions were carried out mainly to check for unusual Bouguer anomalies and when such were discovered the observations were repeated and, if possible, additional observations were made in the environs of the particular station. In the office the final reduction of data was carried out by means of the computer oriented system described by Tanner and Buck (1964). This system was designed to edit as well as reduce the data. About forty-five different error indications ranging from sequence checks to gross checks (e.g., drift rates, etc.) on the data have been incorporated into the program. The principal facts cards for the gravity stations are produced from the program only when all error indications were investigated and the necessary corrections to the observation cards made. The principal facts cards were merged with any existing principal facts cards for the particular area and observations were then plotted and contoured on a map at scale of 1:500,000. Unusual results were checked and the particular observation reprocessed if necessary.

The reduction of regional observations was achieved using two computer programs; Altimeter Reductions and General Gravity Reductions. The first, written by R.K. McConnell of the Dominion Observatory, computed the elevations from the altimeter readings and the output punched onto the detailed cards used in General Gravity Reductions. In reducing the altimeter data, this program applied corrections for temperature, humidity and for atmospheric pressure. The latter correction was determined from successive readings at reference elevations on the assumption that atmospheric pressure varied linearly with time.

The General Gravity Reductions program was used first to calculate the observed gravity values from the gravimeter readings on the assumption that the drift of the gravimeter was linear with time and then to compute the Bouguer anomalies according to the following:

(a) theoretical gravity = $\gamma_t = 978.049\ (1 + 0.0052884 \sin^2\phi - 0.0000059 \sin^2 2\phi)$,

where ϕ is the latitude of the station.

(b) the vertical gradient of gravity = $\frac{dg}{dz} = 0.09406$ mgal/ft

(c) the topography has the form of an infinite sheet with a uniform density of 2.67 g/cm^3.

2-6. Estimated Accuracy of the Measurements

Errors in the Bouguer anomalies stem mainly from errors in the reduced gravity values, the theoretical values of gravity, the reduced elevations, departures of the vertical gradient of gravity and the crustal density from those assumed, and the omission of terrain corrections. Some of these can be estimated by the repetition of observations but others such as the omission of terrain corrections and variations of parameters assumed to be constant can only be estimated dimensionally because the data gathered during the surveys and the topographic information are not sufficiently detailed.

In 1958 about forty of the regional stations scattered throughout the area were marked and repeated to check the accuracy of the observed gravity. The repeated observation was made from a control station and with an instrument other than those used to make the original observation. The r.m.s. difference of these repeated measurements is ±0.2 mgal. This experiment was not repeated during subsequent surveys, but it is likely that the result is representative of all of the gravity measurements with the possible exception of the southerly region where control stations were more frequent and operating conditions less rugged.

It is more difficult to establish an estimate of the accuracy of the altimeter measurements because the reference elevations themselves may contain large errors. Therefore, rather than estimate the accuracy of the altimeter work exclusively, it was decided to check the overall accuracy of the elevations.

Mean sea level in Hudson Bay along the western border of the area and in the Gulf of St. Lawrence to the southeast was suitable for this because the tidal variations were less than five feet. In 1958 and 1959 nearly 100 altimeter connections were made to mean sea level along the shores of Hudson Bay. The r.m.s. departure from mean sea level of these ties is ±20 ft. In 1964, Weaver (1967) made 279 such connections and obtained an r.m.s. difference from mean sea level of ±15 ft. The better result obtained in 1964 is probably a reflection of more frequent and improved reference elevations. From these results errors in Bouguer anomalies due to errors in the elevations would average between ±0.9 and ±1.2 mgal throughout northern Quebec; the latter figure would likely apply throughout the northern part of the region.

Weaver (1967) also conducted an experiment to estimate the overall accuracy of the Bouguer anomalies by repeating gravity stations. Any stations within 0.2 min of latitude and 0.3 min of longitude of each other were regarded as repeated observations. The elevation and the observed gravity of the stations would not be the same, but, in the absence of extremely steep horizontal gradients, the Bouguer anomalies would be about the same. The r.m.s. difference of Bouguer anomalies for 92 repeated observations (the observers were unaware that an observation was being repeated) is ±0.7 mgal. In addition to errors in elevations and observed and theoretical gravities, this figure probably also reflects local variations of the terrain effect and possibly local variations of the vertical gradient of gravity and the crustal density from the constant values assumed.

The accuracy of the other parameters used to calculate the Bouguer anomalies has not been estimated methodically. The values of theoretical gravity probably contain errors between ±0.2 and ±0.5 mgal. The latter estimate would prevail in areas (mainly in the north) where maps at a scale of 1:500,000 were used to scale the latitude and longitude of the stations. Errors in the Bouguer anomalies due to variations of the vertical gradient of gravity from the assumed value of 0.09406 mgal/ft probably do not exceed ±0.2 in most cases. Mean densities of rock samples collected during the surveys (Tanner, 1961; Tanner and McConnell, 1964 and Weaver, 1967) suggest that the crustal density (2.67 g/cm^3) assumed for the Bouguer correction is too low by as much as 0.05 g/cm^3. On this basis the anomalies should be reduced by as much as 0.6 mgal/1000 ft of elevation. This result should be treated cautiously since the estimate takes no account of the surface distribution of the rock types. Gibb (1968) calculated an average density of 2.73 g/cm^3 for all rock samples in northern Manitoba, but when the areal distribution of the rocks was taken into account he arrived at a weighted mean of 2.67 g/cm^3.

It is unlikely that the terrain correction exceeds a few tenths of a milligal for the majority of the gravity stations. The observers were instructed to remove themselves as far as possible from local topographic features, but in a few instances, mainly in the Grenville province and in the northern part of the Ungava peninsula, it was not possible to accomplish this. Tanner and McConnell (1964) considered the terrain effect with respect to two types of terrain (an escarpment and a steeply walled valley) that occur in the Ungava Peninsula. They found that in the case of the steeply walled valley the terrain correction could be as large as 10 mgal. Fortunately, these circumstances occur rarely and it is estimated that the terrain correction exceeds 1 mgal for only about 2% of the stations and that in a few cases terrain corrections of 5 mgal or more may be encountered.

In summary, it seems likely that the results to the south are slightly more reliable than those to the north. Since some of the sources of error have not been estimated, the overall accuracy of the Bouguer anomalies can be estimated only roughly. The Bouguer anomalies south of 52°N are probably accurate to between 1 and 2 mgal and those to the north are generally accurate to 2 mgal.

CHAPTER 3

THE METHOD OF INTERPRETATION

3-1. Introduction

The gravity interpretation presented in this investigation assumes mainly that the anomalous masses are two-dimensional and their density contrasts uniform, but end corrections have been applied in the interpretation of the Weardale anomaly which is used as test of the matrix method described in this chapter. The interpretation is also mainly one of estimating anomalous mass distributions of irregular outline which could give rise to a given anomaly, but a regional isostatic interpretation using the (sin x)/x method is given in Chapter 4. The assumption of two-dimensional structures is reasonable even for the intrusions studied in Chapter 6 because their width is several times their thickness.

Most of the computations have been made using the matrix method described in the next section. The matrix method is an automated procedure which assumes the anomalous mass is subdivided into rectangular blocks. This method has the advantage that an anomaly can be tested for different possible assumptions of background level and density contrast quickly and conveniently to provide some estimate of the limits of these parameters. There is the disadvantage of using rectangular blocks and for this reason polygonal models, based on the results of the matrix method, have been computed using the method of Morgan and Grant (1963).

In the next section the automated matrix method is described. The section is based on a recent paper by Tanner (1967). In the third section of this chapter a brief review of the (sin x)/x method, as it applies to isostatic studies, is given.

3-2 An automated method of model studies in gravity interpretation

3-2-1. General statement

Consider, in two dimensions, a Cartesian system in which the gravity anomaly lies along the horizontal x-axis and has the value $\Delta g(x)$ at the point (x, 0). The z-axis points vertically downward, and the distribution of mass causing the anomaly is represented by a closed body whose surface is cut either twice or not at all by any vertical line. Then the usual problem of gravity interpretation is the solution of the integral equation,

$$\Delta g(x) = \int_{-\infty}^{\infty} K\{(x-\xi), \zeta_1(\xi), \zeta_2(\xi)\} \; \rho(\xi) \, d\xi \, , \qquad (3\text{-}1)$$

where K is the kernel function giving the gravity effect, $\Delta g(x)$, per unit of density contrast of a two-dimensional sheet with upper surface $\zeta_1(\xi)$ and lower surface $\zeta_2(\xi)$ and density contrast $\rho(\xi)$. This is an inverse problem which is non-linear if either $\zeta_1(\xi)$ or $\zeta_2(\xi)$ is the unknown function (Bott, 1967). Since irregularly shaped bodies of specified uniform density contrast are sought, then the non-linear problem must ultimately be solved. In this section a method using the linear solution to iterate the non-linear system is presented.

Two computer programs have been developed from the method: "Sedimentary Basins" and "Granite Bodies". The former approximates basin-shaped structures with flat upper surfaces and the latter approximates bodies with outward sloping contacts and flat lower surfaces. In both cases the density contrast of the anomalous mass is assumed to be uniform. The formulae apply to two-dimensional structures, but three-dimensional structures can be approximated by end corrections (Nettleton, 1940).

3-2-2. The Linear Solution Using Matrices.

In practice, the gravity anomaly is known only at m discrete points over a limited portion of the earth's surface. If the anomalous mass is sub-divided into n ($n \leqslant m$) two-dimensional rectangular blocks then the integral equation (3-1) can be approximated by the finite summation:

$$\Delta g_i = K_{ij} \rho_j, \qquad (i=1 \ldots m, \; j=1, \ldots, n), \qquad (3\text{-}2)$$

where the repeated subscript j indicates that, for each value i, j must be summed over all its possible values. The kernel function can be calculated using the formula giving the gravity effect of two-dimensional rectangular blocks (Heiland, 1940, p. 152).

$$\Delta g = 2G\rho \; \{ -(x-\xi_1)\ln(r_2/r_1)+(x-\xi_2)\ln(r_4/r_3)$$
$$+ \zeta_2 (\phi_1 - \phi_3) - \zeta_1(\phi_2 - \phi_4) \}$$

where the notation has the meaning given in Fig. 3-1. If the depth to the centre of the block is twice the thickness of the block or

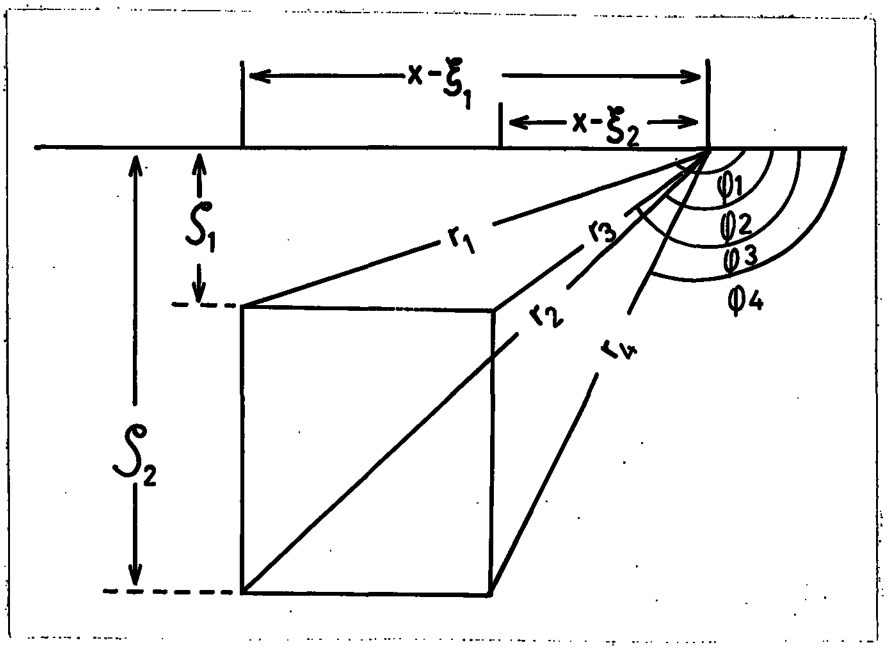


Fig. 3-1

Gravity Effect of a two-dimensional rectangular block.

more, a good approximation to equation (3-3) can be made by assuming the mass to be concentrated in a horizontal plane through the centre of block. Equation (3-3) then reduces to

$$\Delta g = 2G\rho\ (\zeta_2 - \zeta_1)\theta, \tag{3-4}$$

where $\theta = \phi_1 - \phi_3 = \phi_2 - \phi_4$. The use of equation (3-4) in place of equation (3-3) under the condition stated reduces the computation time in a computer by about one-half.

Equation (3-2) defines a system of m equations in n unknowns. If m = n the solution is obtained directly. In matrix notation it is

$$\underline{\rho} = \underline{K}^{-1}\ \underline{g}, \tag{3-5}$$

where K^{-1} is the inverse of the kernel array and g is the array of observed anomalies. If m > n then the method of least squares must be used. For this

$$Q = \sum_{i=1}^{m} (\Delta g_i - K_{ij}\ \rho_j)^2$$

is minimized. This requires that

$$\frac{\partial Q}{\partial \rho_r} = -2\sum_{i=1}^{m} K_{ir}\ (\Delta g_i - K_{ij}\ \rho_j) = 0,\ (r=1\ldots n).$$

This can be rearranged and the sigma notation dropped to give

$$K_{ir}\ \Delta g_i = K_{ir}\ K_{ij}\ \rho_j$$

The solution of this set of equations in matrix notation is

$$\underline{\rho} = \{\underline{K}^T\underline{K}\}^{-1}\ \underline{K}^T\underline{g} \tag{3-6}$$

The solution according to equation (3-5) or equation (3-6) specifies a system of rectangular blocks of variable density ρ_j for a system of horizontal two dimensional sheets of variable mass/unit area of which can give rise to the observed anomaly. The corresponding distribution of blocks of uniform density contrast ρ can be estimated by assuming either the upper surface or the lower surface of the blocks to be fixed and transforming on the basis that the mass of the blocks remains constant. Since the gravity effect is non-linear with depth, this system of transformed blocks cannot satisfy the observed anomaly, even approximately, unless the differences in thickness between the transformed and the untransformed blocks are all relatively small. Consequently it is usually necessary to adjust the set of transformed blocks. The details of the adjustment vary with the type of structure approximated: the linear approximation is used, but precautions to avoid instability are required.

The next sections are devoted to the application of this linear theory to generate structural models whose outlines approximate sedimentary basins and granite bodies as defined earlier.

Given the local anomaly at m descrete points over the earth's surface, the depth to the upper surface and the density contrast ρ, the problem can be reduced to:

(a) first estimating a distribution of blocks of uniform density contrast, and

(b) adjusting the thickness of the blocks to satisfy the given anomaly.

Except for minor variations the method used to provide the first estimate is the same for both programs. Both programs allow the interpreter to provide his own first estimate of the distribution of blocks, in which case only step (b) will be executed.

Examples from both programs are presented in sub-section (3-2-5).

3-2-3. The first estimate.

The first step involves estimating the thickness of the blocks of uniform density contrast and arranging their distribution to approximate a sedimentary basin or a granite body as defined previously.

Initially the mass giving rise to the anomaly is assumed to be concentrated in a thin horizontal sheet along the specified upper surface of the structure. The solution of either equation (3-5) or equation (3-6) then provides an equivalent layer as shown in Fig. 3-2. In this diagram the surface mass given by the matrix method is compared to that obtained by the (sin x)/x method (Tomoda and Aki, 1955) in which the observed anomaly, sampled at uniform intervals along the profile, is continued downward to a horizontal plane and the corresponding surface mass distribution along that plane determined from the equivalent layer theorem. For the example shown in Fig. 3-2 the observed anomaly is sampled at intervals of 2000 m which is the (sin x)/x equivalent of the 2000 m block width used in the matrix method. As Fig.3-2c shows, the two methods agree to within one or two per cent except at the ends of the profile. The disagreement at either end is due to the assumption in the (sin x)/x method that the observed anomaly is zero beyond the ends of the profile.

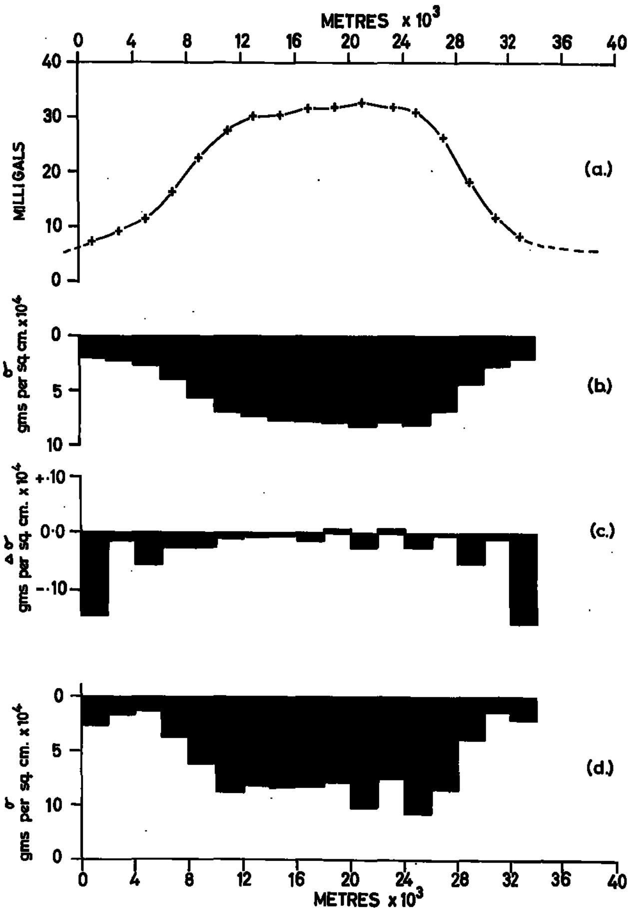


Fig. 3-2.

The equivalent layer and the matrix method. Part (a) shows the observed anomaly and (b) the surface mass at a depth of 500 using a block width of 2000 m. Part (c) gives the differences in surface mass between the matrix and the (sin x)/x. The surface mass at a depth of 2000 m (block spacing 2000 m) is shown in part (d). Note the onset of instability when the depth to the upper surface equals the block width.

This equivalence of the matrix method and downward continuation techniques suggests that some precaution should be taken to avoid excessive amplification of local components of the anomalous field. This can usually be done by choosing a block width which is greater than the depth to the buried horizontal plane. Fig. 3-2d gives the equivalent layer by the matrix method when the depth to the upper surface equals the block width. Incipient instability is shown. When the upper surface is placed at even greater depths, local components are further amplified and instability becomes more pronounced, which indicates that the practice of choosing block widths greater than the depth to the upper surface should usually be adopted.

The last part of this first estimate requires that blocks of uniform density contrast ρ be obtained. In the sedimentary basin program the upper surface is known and the lower surface is unknown. The latter is estimated using the relation

$$\zeta'_{2j} = \zeta_{1j} + \sigma_j/\rho \ , \quad (j=1\ldots n). \tag{3-7}$$

In the granite bodies program the upper surface is given for a specified block (the kth) and the upper surface of all other blocks and the flat lower surface are unknown. The lower surface of all blocks is estimated using the relation

$$\zeta'_{2j} = \zeta_{1k} + \sigma_k/\rho \ , \quad (j=1\ldots n). \tag{3-8a}$$

The upper surfaces are then obtained by:

$$\zeta'_{1j} = \zeta'_{2j} - \sigma_j/\rho \ , \quad (j \neq k) \tag{3-8b}$$

3-2-4. <u>The adjustment of the model</u>

In the adjustment of the first estimate a method which converges quickly and remains stable is desired. Stability has proved more of a problem with the sedimentary basin program. Consequently two methods of adjustment have been incorporated into this program.

The first of these two methods is as follows:

(a) calculate the gravity effect of the system of the blocks obtained from the first estimate and determine the residual anomaly at each point of observation,

(b) place a thin sheet at the base of each block and, using the residual anomalies, calculate the σ_j by the matrix method, and

(c) transform the σ_j to give the adjustment in terms of a small block of density contrast ρ, to be added or subtracted from that given by the first estimate according to the sign of σ_j.

This process can be continued until the residuals are within the limits desired. This method (method 1) converges quickly and usually only one or two adjustments are necessary. However, it can be occasionally unstable. Since the mass necessary to adjust the blocks is assumed to be concentrated in a thin sheet at the base of each block and since the gravity effect is non-linear with depth, the amount of mass to be removed from any block is always overestimated. When large "negative" adjustments are required the system can become unstable, since in satisfying the residual anomalies it must compensate by adding in mass elsewhere. A second type of instability arises when the observed anomaly cannot be fitted to any model with the specified density contrast and upper surface. This occurs if the upper surface is too deep or the density contrast too low.

A more stable, but more slowly converging method (method 2) is to use the entire transformed block given by the first estimate to adjust the model. This averages the adjustment throughout the whole block and, consequently, instability is unlikely. After each adjustment a new set of transformed blocks can be obtained using the relation:

$$\zeta'_{2_j} = \zeta_{1_j} + (\zeta_{2_j} - \zeta_{1_j})\, \rho_j/\rho \quad (j=1\ldots.n), \tag{3-9}$$

where the primed co-ordinate again refers to the estimated value. This method does not require a knowledge of the residuals and a solution is given when ρ_j is everywhere equal to or nearly equal to the assumed density contrast ρ . However, the residuals to indicate directly the quality of the solution and are always computed in practice.

In the granite bodies program only the upper surface of the kth block is fixed and it is usually necessary to adjust the upper surface of all other blocks and also the depth to the base of the structure.

Method 1 is adapted to granite bodies as follows:

(a) determine the residual anomalies,

(b) place a thin sheet along the upper surface of each block (the kth excluded) and across the base of the structure, and

(c) calculate the ρ_j and transform using the relation

$$\zeta'_{1j} = \zeta_{1_j} - \sigma_j/\rho, \quad (j\neq k), \tag{3-10a}$$

for the upper surfaces and

$$\zeta'_{2j} = \zeta_{2_j} + \sigma_k/\rho, \quad (j=1\ldots.n), \tag{3-10b}$$

for the lower surface.

Thus far, method 1, as applied to granite bodies, has not shown instability. The reason for this seems to be that the adjustment is made to the upper surface of the blocks (except for the wide kth sheet). Since these adjustments are usually small, instability due to overestimating the mass to be removed is unlikely. The kth sheet at the base of the structure is usually wider than the depth to it and will not reflect the presence of local components in the observed anomaly.

Both programs will continue to adjust the model until either the residuals are everywhere less than that specified by the interpreter, or the number of adjustments desired by the interpreter has been completed. After each iteration the dimensions of the model and the residuals are printed.

3-2-5. Examples

Since the sedimentary basin program gives a result that is nearly identical to that produced by Bott's (1960) method, the application given here is aimed at demonstrating a procedure that can be used for structures not exposed at the earth's surface. In this situation there is usually no direct information available regarding the overall width of the structure. Although it is possible to estimate the width of the structure and proceed with the program, it may be more prudent to proceed as follows:

(a) assume all blocks have the same width, preferably one that is greater than the depth to the upper surface,

(b) centre one of the blocks under the extreme value of the observed anomaly, and

(c) assume the blocks extend from this central point to either edge of the anomaly.

This approach is demonstrated in Fig. 3-3 for a hypothetical structure, 60 km wide and 4 km thick, at the base of the earth's crust. The anomaly produced by this model, assuming the density contrast to be 0.5 g/cm^3, is shown in Fig. 3-3a. The procedure outlined above was applied to this anomaly using a block width of 50 km and the structure derived (Fig. 3-3d) by the sedimentary basins program satisfied the given anomaly to within 0.3 mgal everywhere (Fig. 3-3c). This provides a reasonable interpretation of the anomaly.

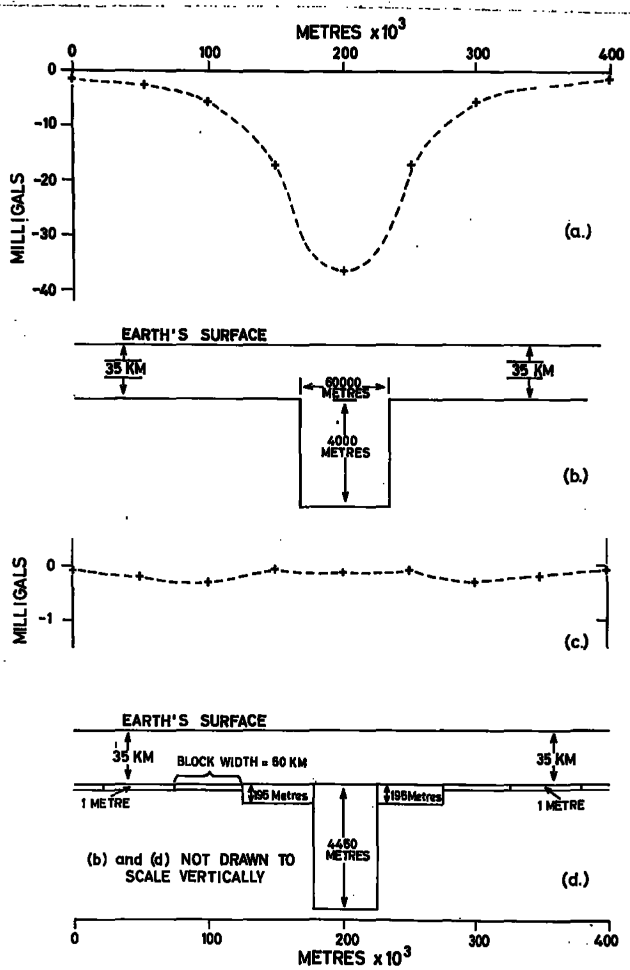


Fig. 3-3

The application of the matrix method to buried structures using a hypothetical structure at the base of the earth's crust as an example. The structure assumed is shown in (b) and the anomaly it produces in (a). The model produced by sedimentary basin program is shown in (d) and the residuals in (c).

The granite bodies program has been applied to the anomaly over the Weardale granite in northeast England. Although not exposed, the presence of a granite has been established by drilling at Rookhope in County Durham. The local anomaly shown in Fig. 3-4a is taken from Bott (1956) with the background level of the regional field assumed to be 10 mgal. The structure is approximated by 10 blocks.

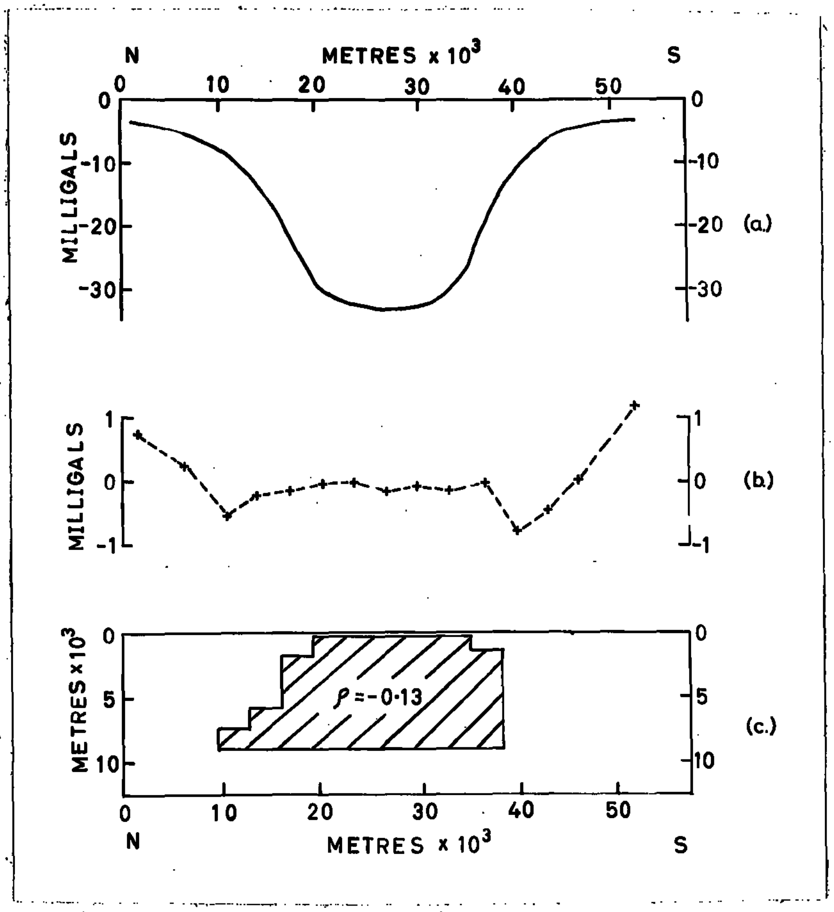


Fig. 3-4

The interpretation of the Weardale granite in northeastern England using the granite bodies program. The model is assumed to have a strike length of 10,000 m in either direction from the plane of the profile. The local anomaly is shown in (a), the residuals in (b) and the model in (c).

TABLE 3-1

MODEL OF WEARDALE GRANITE

BLOCK	LEFT SIDE METRES	RIGHT SIDE METRES	UPPER SURFACE METRES	LOWER SURFACE METRES
1	9600	12800	7400	8970
2	12800	16000	5730	8970
3	16000	19200	1770	8970
4	19200	22400	380	8970
5	22400	25600	490	8970
6	25600	28800	400**	8970
7	28800	32000	380	8970
8	32000	35200	420	8970
9	35200	38400	1470	8970
10	38400	41600	8969	8970

*All blocks assumed to have a strike length of 10 km, in either direction Normal to plane of profile.
**This surface not adjusted.

each of which is 32000 m wide, with the upper surface of block 6 (Table 3-1) fixed at 400 m. All blocks are assumed to have a strike length of 10000 m in either direction from the plane of the profile and a density contrast of 0.13 g/cm^3. The suggested outline of the granite mass Fig. 3-4c is roughly that of a trapezium with the north face at about 45° and the south face dipping steeply. The depth to the base of the granite is about one kilometre greater than that obtained by Stacey (1965) who assumed a two-dimensional structure.

The residual anomalies (Fig. 3-4b) are systematically positive at the ends of the profile which suggests that either the background level assumed is in error by about a milligal or the density contrast assumed is too low. It is probable that the background level is in error for reasons given by Bott and Masson-Smith (1957).

3-2-6. Discussion

One disadvantage of the present method is the anomalous mass is represented by rectangular blocks. It may be possible to alter the programs to produce structures which are polygonal in outline. A second disadvantage is the need to avoid block widths less than block depths which may exclude the investigation of a given anomaly in detail.

3-3. The (Sin x)/x Method

This useful technique was first published by Tomoda and Aki (1955), but seems strangely neglected in the literature. It provides a simple means of estimating, from a given anomalous gravitational field, the corresponding subterranean mass distribution, assumed to be concentrated on a horizontal plane at given depth. It can also be used to calculate isostatic anomalies, vertical gradients, deflections of the vertical and undulations of the geoid. In this investigation the method is used to calculate two-dimensional isostatic anomalies. Since the method is not widely known a brief summary of its derivation in two dimensions is given here. In addition to the original paper by Tomoda and Aki, an excellent summary of the method and its applications is given by Shimazu (1962).

It can be shown from potential theory that if, in a Cartesian system, the gravity anomalies along some plane surface are expressed in terms of their Fourier components, the anomaly field can be continued downward by means of the relation

$$\Delta g(x)_{z=d} = \sum_k A_k \begin{matrix} \cos kx \\ \sin kx \end{matrix} e^{kd}, \qquad (3\text{-}11)$$

where k is the wave number and d the depth to the surface to which the downward continuation is made. This can be expressed in terms of the surface mass, σ, through the equivalent layer theorem which states that

$$\Delta g(x)_{z=d} = 2\pi G\sigma(x)_{z=d}$$

Substitution into equation 3-11 gives

$$\sigma(x)_{z=d} = \frac{1}{2\pi G} \sum_k A_k \begin{matrix} \cos kx \\ \sin kx \end{matrix} e^{kd} \qquad (3\text{-}12)$$

This is the equation giving the subterranean mass distribution derived by Tsuboi (1938). Its solution requires that the constants A_k be evaluated by Fourier analysis. As Tomoda and Aki have shown this can be avoided by introducing the function sin x/x. This function has the value 1 when x=0 and vanishes when $x=n\pi$, n being any positive or negative integer different from zero. If the gravity anomalies are given at equally spaced intervals along the earth's surface, we can define this interval to be π radians of angular measurement and, from the property just given, the anomalies can be represented by the series

$$\Delta g_{x=n\pi} = \sum_{s} \Delta g_s \frac{\sin(n-s)\pi}{(n-s)\pi} \tag{3-13}$$

For any particular value of x the right hand side of equation (3-13) only has a value different from zero when s = n, which is the value of the anomaly at that grid point. Therefore, summation over all possible values of s for each value of n specifies the anomaly at all grid points.

The other property of (sin x)/x that is important to the argument is its capacity to act as a low pass filter. The Fourier cosine transform shows that its spectrum is very simple; it has the value 1 for $0 \leq m \leq 1$ and 0 for $m > 1$. Thus, all wavelengths less than twice the grid distance are suppressed. This eliminates the effect of local components in the gravitational field and insures that the downward continuation will converge uniformly (c.f., Grant and West, 1965). Writing (sin x)/x in terms of its Fourier cosine integral we get

$$\frac{\sin x}{x} = \int_0^1 \cos kx \, dk \ . \tag{3-14}$$

The solution to the problem now follows directly. From equations (3-13) and (3-14) and the equivalent layer theorem, the surface mass, as given by the downward continued gravity field, is

$$\sigma\,(n)_{z=d} = \frac{1}{2\,\pi G} \sum_{s} \Delta g_s \int_0^1 \cos k(n-s)\pi \; e^{kd} dk.$$

This can be integrated by parts to give

$$\sigma\,(n)_{z=d} = \frac{1}{2\,\pi G} \sum_{s} \Delta g_s \overset{0}{\phi}_{n-s}, \qquad (3\text{-}15)$$

where

$$\overset{0}{\phi}_{n-s} = \frac{d'}{\pi\{d'^2+(n-s)^2\}} \{ \pm e^{d'\pi} -1\} , \quad (n-s) \begin{matrix}\text{even}\\ \text{odd}\end{matrix} \qquad (3\text{-}15b)$$

Since the grid spacing has been defined in terms of angular measure so must the depth. The depth in radians is given by the ratio of the depth to the surface and the grid interval times π. This conversion has been made in equation (3-15b). The $\overset{0}{\phi}$ function needs only to be evaluated once for any problem. The repeated application of the convolution or overlapping sum given in equation (3-15a) at each grid point then gives the subterranean mass distribution.

The isostatic gravity anomaly is defined as

$$\Delta g_{iso} = \Delta g - \Delta g', \qquad (3\text{-}16)$$

where Δg is the Bouguer anomaly and $\Delta g'$ the gravity effect of the mass, at depth, compensating for surface irregularties. The mass of the crust above sea level can be expressed in terms of the Fourier components of the elevation and the density of the crust. From Airy's hypothesis this must be compensated by the negative of this mass at the base of the earth's crust. Through the equivalent layer theorem the corresponding gravity effect along a plane at the base of the crust can then be given. Since we wish to know the gravity effect at the surface of the earth, the gravity effect at the base of the crust must be continued upward to give $\Delta g'$. As the mass, and hence the gravity effect, at the base of the crust is expressed in terms of its Fourier components the upward continuation can be effected by multiplying by e^{-kd}. The isostatic anomaly is then

$$\Delta g_{iso}(x) = \Delta g(x) + 2\pi G\rho \sum_k H_k \begin{matrix} \cos kx \\ \sin kx \end{matrix} \; e^{-kd}. \tag{3-17}$$

As before the function sin x/x can be introduced to give

$$\Delta g_{iso}(n) = \Delta g \;(n) + 2\pi G\rho \sum_s H_s \int_0^1 \cos k(n-s)\pi \; e^{-kd} dk$$

where H_s is the surface elevation referred to mean sea level.

Upon integration we get

$$\Delta g_{iso}(n) = \Delta g(n) + 2\pi G\rho \sum_s H_s \phi^1{}_{n-s}, \tag{3-18a}$$

where

$$\phi'_{n-s} = \frac{d'}{\pi(d'^2+(n-s)^2)} \{ \pm e^{-d'\pi} - 1 \}, \quad (n-s) \begin{matrix} \text{even} \\ \text{odd} \end{matrix} \tag{3-18b}$$

Again 3-3-9 assumes that d is given in terms of its angular measure. Both ϕ^0 and ϕ' are symmetrical about the origin (n-s = 0) and $\sum_{-\infty}^{\infty} \phi^0 = \sum_{-\infty}^{\infty} \phi' = 1$

Shimazu used the (sin x)/x method to give isostatic anomalies along east-west profiles across the Canadian Shield and the Cordilleran Mountain belt in Western Canada. His results compare well with those computed by classical methods described by Heiskanen and Vening Meinesz (1958). However, an error in applying the method appears in one example. The mean crustal depression (1.4 km) of an actual crust having a mean elevation $\bar{H}$ (320 m) was added to the mean crustal thickness of 35 km. Isostatic anomalies were apparently then calculated using the observed Bouguer anomaly and the elevation referred to mean sea level. However, since part of the isostatic effect has been taken into account in calculating the mean crustal depression only residuals should be considered in the calculations employing the (sin x)/x method. Specifically the quantities used in equation (3-18a) should be

$$\Delta H_s = H_s - \bar{H}$$

and $\Delta g_n = \Delta g_n + 2\pi G \rho \times$ mean crustal depression. In this work the calculations have been made assuming a mean crustal thickness of 35 km, the observed Bouguer anomaly and the observed elevation.

Computer programs have been written to calculate the subterranean anomalous mass as defined by equation (3-15) and the isostatic anomaly as defined by equation (3-18a). The specifications for the programming are given in Appendix 2.

CHAPTER 4

DESCRIPTION AND CORRELATION OF GEOPHYSICAL, GEOLOGICAL AND TOPOGRAPHIC DATA

4-1. Introduction

This chapter is intended to provide the background pertinent to the interpretation of the gravitational field in northern Quebec. It is again emphasized that this discussion will be restricted to a description of the major regional features or characteristics of the region and that any detailed information necessary for the interpretation will be introduced when required during the interpretation.

In the past such things as remoteness and complexity of the geology have contributed to the lack of adequate geological maps and this has been a handicap to geophysical studies generally. This has been particularly so for gravimetric studies where a knowledge of the surface geology is essential to most such investigations. In recent years expanded field programs, backed up by more extensive and more powerful laboratory methods, have slowly improved the state of geological knowledge so that regional geological maps exist for most areas in northern Quebec and the classification of the rocks exposed is broadly understood and agreed to by most geologists. This statement is perhaps less true in the more geologically complex areas such as the Grenville province but even here the information availabe is such that geologists are now in a position to advance general theories on the history of the area (Wynne-Edwards, 1964) and to suggest problems that appear important to unravelling the geological history. Although adequately detailed data on the distribution of the surface rocks is in many cases lacking there is sufficient known of the geology in most areas that gravimetric data can be used to provide preliminary estimates of the subsurface distribution of some of the larger geological features in Quebec and to suggest areas where concentrated efforts by geologists might be fruitful.

The increased use of laboratory facilities as an integral part of any field study has turned up some surprising misconceptions in older geological literature. For example a large basic intrusion near Duluth has been for years called the "Duluth gabbro", but at a recent symposium a paper presenting the results of a detailed petrological and geochemical study showed that the mineralogy is very similar to that found in the anorthosite and gabbro (hereafter called anorthositic) intrusions in the Grenville of Quebec and that the term "gabbro" is probably misapplied. Undoubtedly future laboratory studies carried out in conjunction with more comprehensive field studies will turn up more surprises of this nature.

The geological nomenclature is neither unanimously agreed to nor uniformly applied in northern Quebec. Two examples will serve to demonstrate this. In Chapter 1 the terms "belt, trough and front" were used when referring to the structural boundaries present in northern Quebec. Other names for these features are being used and may well come into common usage in the near future. At present these names appear most widely used and known and, as is the practice with respect to geographical names, will be used here. Another example is the term "Grenville province". There are geologists, for example, who prefer the term "Grenville sub-province" because many of the rocks found in the Grenville region are apparently more highly metamorphosed equivalents of rocks found in other provinces. However, the rocks of the Grenville do comprise a unit whose structure and petrology are broadly different and whose rocks do give K-Ar ages different from those of the other geological provinces. It would then appear more reasonable to use the term "province" for the Grenville also. There are, of course, other examples of this that could be cited, but instead it is reiterated that terms apparently most commonly used will be employed.

4-2. General Geology

4-2.1. Introduction

Prior to the 1950's geologists engaged in Precambrian mapping had concentrated on the development of a system which subdivided into eras and units similar to that used to classify post-Precambrian rocks. This system of classification was not satisfactory and in the late 1940's Wilson (1949) and Gill (1949) independently proposed that the Canadian Shield be subdivided into geological provinces on the basis of existing radioactive age determinations and structural characteristics. Subsequent age determinations, mainly by the Geological Survey of Canada, by the K-Ar method have developed this system to the point where it is widely accepted as a working basis to-day.

Stockwell (1962) has recently incorporated the data from radioactive age determinations into a system classifying the rocks of the Canadian Shield. The K-Ar ages within the geological provinces (Fig. 1-1) group remarkably well about one of three ages - 2500 my, 1700 my, and 950 my. These dates are taken to be evidence for three main orogenic periods which are respectively called the Kenoran, the Hudsonian and Grenville orogenies. Rocks giving Kenoran ages belong to the Archaean era, while those given Hudsonian and Grenville ages are classified as Proterozoic. It is worthwhile at this point to note, in credit to the earlier work of Precambrian geologists, that the concept of relative ages inherent in the pre-1949 system was correct if one excludes the Grenville which was, and still is, controversial. The criteria used prior to 1948 to distinguish between rocks of the two eras were stratigraphic relationships, degree of metamorphism and general character of the rocks. With the possible exception of metamorphism these criteria are generally valid to-day. In the case of character of the rocks the major difference seems to be that the Proterozoic rocks contain a much higher proportion of the so-called clean sediments - sandstones, quartzites and limestones.

The description of the geology which follows is based largely on summaries given by geologists active in a particular region. These summaries are in turn based on detailed studies, too numerous to mention here, carried out mainly by members of the Geological Survey of Canada, and the Department of Natural Resources, Quebec. No rigorous order will be followed in presenting the description, in an effort to concentrate on the major characteristics of each province. The detail of the description of each province will vary with the amount of detailed geological data available for each province and there will undoubtedly be overlap between this section and subsequent sections given in connection with the interpretation.

4-2-2. The Superior Province

The Superior province forms the core of the Canadian Shield with the younger geological provinces located on its periphery. In northern Quebec it is located approximately between latitude 52°N and 61°N and is bounded on the east by younger rocks at about longitude 68°W. The Superior province continues to the west of northern Quebec and underlies nearly all of northern Ontario. It is also the apparent oldest of the geological provinces with the mean K-Ar age about 2500 my. This plus the fact that it forms the core of the Canadian Shield have led to the theories of continental accretion frequently mentioned in the literature.

The Superior province in Quebec differs significantly from that to the west where it can be broadly considered to consist of gneisses and granites with infolded belts of volcanics and sediments (greenstone belts), overlain by younger less contorted sediments and volcanics of Proterozoic age. The grade of metamorphism is generally low throughout this part of the Superior province. In northern Quebec on the other hand the greenstone belts are almost totally absent and there are only scattered occurrences of overlying younger sedimentary and volcanic rocks. In addition, there are numerous occurrences of high grade metamorphic rocks of the granulite facies (Stevenson, 1962, 1965; Eade, 1966), particularly in the northern part of the Superior province, south of the Cape Smith Belt. The relationship of the granulites to the granites and gneisses in the far north give the impression that the latter are remnants of an overlying "layer" of lower grade metamorphic rocks. The granulites are considered by Eade, Fahrig and Maxwell (1966) to be in the lower range of the granulite metamorphic facies.

The presence of granites and greenstone belts is normally considered by geologists to represent a "higher crustal level" than high grade metamorphic rocks such as granulites and the relatively greater abundance of the latter in northern Quebec can be interpreted as representative of a deeper erosional level. Comparisons of chemical analyses of the rocks in Quebec with those for other areas of the Canadian Shield and other shields should provide a means of studying very generally the effects of regional metamorphism on the vertical distribution of elements within the crust. Several such studies are available for this purpose, but of particular interest is that of Eade, Fahrig and Maxwell (1966) who have carried out a comprehensive geochemical study of the northwestern quarter of northern Quebec, at the same time comparing their results to those of various other authors. One of these comparisons (Table 4-1), made with the results of Reilly (1965) who presented mean results for the rock samples systematically collected throughout the Precambrian of northern Ontario, indicates that the rocks of northern Quebec are more basic than those of northern Ontario, the major difference being a lower average silica content in northern Quebec.

TABLE 4-1

SOME RESULTS OF PRECAMBRIAN GEOCHEMICAL STUDIES

	NORTHERN QUEBEC EADE ET AL (1966)	ONTARIO REILLY (1965	ALL SHIELD AREAS POLDEVAART (1955)
SiO_2	64.5	66.3	66.4
Al_2O_3	16.1	15.4	15.5
Fe_2O_3	1.5	1.3	1.8
FeO	2.9	2.9	2.8
MgO	2.3	2.1	2.0
CaO	3.3	4.0	3.8
Na_2O	4.0	3.9	3.5
K_2O	2.8	2.3	3.3
H_2O	0.8	0.9	--
TiO_2	0.5	0.5	0.6
P_2O_5	0.2	0.1	0.2
MnO	0.1	0.1	0.1
CO_2	0.2	0.2	--

A comparison (Table 4-1) with Poldevaart's (1955) average for all shield rocks also emphasizes the basic character of the rocks of northern Quebec which are slightly lower in silica, calcium and potash than the average values for all shield rocks. A geochemical study by Shaw (1967) based on rock samples collected by Observatory field parties in the region to the east and south of that investigated by Eade et al also indicates that the rocks in northern Quebec are on the average slightly more basic than shield rocks elsewhere. These results along with the arguments in support of the presence of a deeper erosional level have led Eade et al to conclude that the difference in average chemical composition probably reflects chemical zoning caused by the transport of low temperature constituents to higher crustal levels during regional metamorphism. The only alternative to this interpretation would seem to be that the eastern part of the Superior province in Quebec has had a different geological history from that to the west and presumably from other shield areas. In any event, the current study in the area of the dividing line between the two regimes within the Superior province takes on added importance. This line is approximately marked by a north-south trending positive gravity anomaly called the Kapuskasing High (Innes, 1960) and by a similarly trending belt of magnetic anomalies. Although the cause of these anomalies is not completely understood it is interesting to note that recent geological studies by the Ontario Department of Mines have revealed a more widespread occurrence of granulites along the axis of the gravity anomaly than hitherto observed.

Very generally the surficial distribution of rocks in northern Quebec can be summarized as follows:

(a) a central core of predominantly granodioritic gneisses in the area east of James Bay,

(b) granodioritic gneisses with increased abundance of granulites in the areas to the north, east and southeast of (a),

(c) a complex assemblage of gneisses and granites, Keewatin greenstone belts and Temiskaming sediments in the vicinity of the well known mining belts centred around Timmins, Kirland Lake and Rouyon to the southeast - these rocks are broadly typical of much of the Superior province in Ontario.

Radioactive age determinations (K-Ar) range from about 2200 my to 2700 my. The average age for all measurements is about 2500 my.

4-2-3. The Churchill Province. This province borders the Superior province on the north and the east; its contact with the latter is a fold belt in each case. To the north is the Cape Smith Belt which in recent years has been of interest to the mining industry; commercial deposits of asbestos and nickel have been developed and exploration of at least one other nickel deposit is currently in progress. To the east is the Labrador Trough which is well known for its vast deposits of iron ore. Of the two the Labrador Trough has been subjected to the most intensive study. Field studies in the Trough date back to the work of A.P. Low - a geologist with the Geological Survey of Canada - around the turn of the century. More recent studies have been concentrated in the Schefferville (Knob Lake) area because of the huge iron ore deposits located there. Work on the Cape Smith Belt also dates back to the early part of this century, but it was not until the late 1950's when economic interest in the area developed, that detailed mapping by the Quebec Department of Mines of the area began. This work was discontinued in the 1960's before the belt was completely mapped.

The description of the Cape Smith Belt given here is based on a summary of the geology given by Bergeron (1957). Summaries of the geology of the Labrador Trough have been given by Bergeron (1957) and Fahrig (1957) for the northern and southern portions of the Labrador Trough respectively. Bergeron (1965) has also given a summary of the geology of the Labrador Trough based on the stratigraphy given by Frarey and Duffell (1964) for the southern half of the Trough. Although the succession stated by Frarey and Duffell is valid for the Schefferville area, Bergeron gave tentative correlations with the other portions of the Labrador Trough. The subdivision includes groups and formations but for this work a brief discussion of the groups will suffice.

The Cape Smith Belt, which extends across the northern part of the Ungava Peninsula, is of Proterozoic age and varies in width from about 60 km in the west to 15 km in the west. The nature of its contact with the Archaean rocks of the Superior province to the south is not completely certain; it is regarded by some geologists as an unconformity and by others as a low angle thrust fault. To the north its contact with Proterozoic paragneisses is probably a fault. These paragneisses, which have not been mapped in detail, extend to the shores of Hudson Strait.

The general succession of the Cape Smith Belt can be described as sedimentary rocks interbedded with and overlain by lavas, both of which have been intruded by basic and ultrabasic intrusions. The sediments consist of dark slates and impure limestone with intercalated tuffs. The volcanics, which are mainly basic and both pillowed and massive, are similar to those found in the Keewatin greenstone belts. The intrusive rocks which are usually concordant, are usually gabbroic, but serpentinites have been mapped in the central region of the belt.

The Labrador Trough extends north from the Grenville Front at approximately 53°N for a distance of about 800 km; its northern extremity is located at about 61°N. It is roughly 80 km wide between Fort Chimo and its southern limit; north of Fort Chimo it gradually tapers off until it disappears north of Payne Bay. In plan view it can be divided into western sedimentary and eastern igneous portions of roughly equal width. Throughout most of the Labrador Trough the oldest rocks belong to the Knob Lake Group which consists of quartzites, slates, calcareous rocks, the well known iron formation and minor volcanic rocks. Next in the succession is the Doublet Group which is comprised of basic volcanic rocks with intercalated sedimentary strata. The intrusions within the Labrador Trough belong to the Montagnais Group and are mainly basic and ultrabasic intrusions. One formation of this group (Wakuach) contains a blotchy gabbro ("leopard rock") which has been prospected extensively for base metals. The youngest Precambrian rocks are the sediments of the Sims Formation. Overlying the section locally is the Mesozoic Redmond Formation which consists of clays, ferrugenous argillites and rubble ore.

The above succession is generally true for most of the Labrador Trough. The major exception occurs in the vicinity of Cambrian Lake, located at about latitude 58°N, where a very thick series of continental sediments, which Dimroth (1964) has named the Chakonipau Formation, underlies the rocks of Knob Lake Group.

The detailed structure of the Labrador Trough is complicated and several prominent thrust faults exist within the feature. It is probably because of the complex nature of the structure that no overall estimates of the thickness of the Trough rocks has been given in the literature.

The western boundary of the Labrador Trough is considered by Fahrig (1957) to represent the erosion reduced remnant of a large area of sedimentary rocks which originally extended much further to the west. He interprets the presence of slates in the upper part of the sedimentary sequence as indicative of a very broad area of deposition and of a tectonically neutral zone in the region of the present boundary. The eastern boundary of the Labrador Trough has long been considered to be faulted and hence the use of the term "trough". In this context both Fahrig (1957) and Bergeron (1957) have suggested that the term "trough" may be a misnomer for two reasons:

(a) the grade of metamorphism increases greatly from west to east across the Labrador Trough and into the gneisses and schists to the east,

(b) the schists and gneisses immediately to the east of the Labrador Trough appear in places to be more intensely metamorphosed equivalents of the rocks of the Labrador Trough.

This conclusion is not supported by the work of Beall, Hurley, Fairburn and Pinson (1963) who carried out a whole rock Rb-Sr age determination on a sample of the schists to the east of the Labrador Trough. This sample gave an age of 2450 my; an age which is about the same as that for the basement to the west of the Labrador Trough. This result suggests the basement to the east and west formed a continuous platform and that the term "trough" may be appropriate.

In additon to the result described above Beall et al (1963) carried out a reasonably comprehensive program of dating radioactively (K-Ar and Rb-Sr) the rocks of both the Labrador Trough and the Cape Smith Belt. The sequence of events emerging from this study is one of an early disturbance prior to 2000 my followed by sedimentation and perhaps other minor disturbances and a great orogeny at about 1600 my followed by a minor orogeny at 1400 my. The history of the Cape Smith Belt seems to differ from that of the Labrador Trough in that two periods of sedimentation and extrusion apparently occurred in the Cape Smith region.

4-2-4. The Grenville Province.

This province crops out along a northeast trending belt, approximately 350 km wide, in the southern part of the map area. Its northern contact with the Superior province to the north is the well known "Grenville Front". Its southern contact is also a thrust fault, Logan's Line, which over most of its length lies beneath the St. Lawrence River and the Gulf of St. Lawrence. South of Logan's Line are the folded rocks of the Appalachian system which are of Palaeozoic age.

In this study it is only the nature of the Grenville province and the Grenville Front that is of interest.

Geological studies of the Grenville, the most complex and least understood of all the provinces of the Canadian Shield, date back to the mid-nineteenth century and the work William Logan and other geologists of the Geological Survey of Canada (G.S.C.). Since that time geologists of the G.S.C., the Quebec Department of Mines, and various Canadian and American univerisity geologists have all joined the fray in an attempt to map and to draw a coherent picture of the Grenville province. In the last decade there have been various attempts to describe the broad characteristics of the Grenville. The first of these was a symposium held under the aegis of the Royal Society of Canada. Subsequent symposia held by the Royal Society of Canada on the Proterozoic rocks of Canada and the tectonics of the Canadian Shield also contain general papers on the Grenville. Finally, Wynne-Edwards (1964) presented an interpretation based mainly on an analysis of structural data gathered in the Grenville province. This paper prompted a discussion of the paper by Appleyard (1965) who agreed with main conclusions of Wynne-Edwards but disagreed with the arguments used to reach these conclusions. The various symposia and papers have not resolved the Grenville problem, but have brought the main theories concerning the Grenville into sharper focus. One of these theories holds that the Grenville is truly composed of younger rocks which have gone through a normal tectonic cycle. The other, that of Wynne-Edwards, regards the Grenville as older rocks recycled during the Grenville orogeny about one billion years ago. The hypothesis of continental accretion, of which the Grenville is perhaps the cornerstone, also hangs in the balance with the fate of the former theory.

There is no one sequence of rocks that can be regarded as typical throughout the entire Grenville province. It is true that in different parts of the Grenville a certain type of rock(s) is typical for that area and in Quebec the Grenville can be subdivided broadly into an Ottawa region and a very much larger eastern region. Osborne and Morin (1962) have further subdivided the Ottawa region into two sub-regions or sub-provinces. Their Grenville A sub-province lies to the south and contains the type locality originally studied by Sir William Logan and his associates. Here there is a recognizable stratigraphy containing marble, crystalline limestone and a charnokitic-anorthositic suite of rocks. The Grenville B subprovince to the north consists of rocks which are similar in character to the rocks of the Superior province, but which are more highly and irregularly folded and more highly metamorphosed (amphibolite facies) than their apparent Superior equivalents.

The eastern region, which includes 90% or more of the Grenville in Quebec, is characterized by what Wynne-Edwards has called "blob geology". Structures do not have uniform trends or plunges, but instead appear as isolated patches or "blobs". A good example of this can be found south of the Labrador Trough where detailed geological mapping has failed to produce a recognizably coherent distribution of the iron formation although, as Wynne-Edwards points out, it is apparent that this was at one time a continuous stratigraphic unit. According to Wynne-Edwards discontinuous structural patterns are typical of areas which have been folded in different directions and he concludes that the rocks exposed northeast of Ottawa are part of a recycled pre-Grenville basement.

The rock types exposed in the northeastern Grenville differ significantly from those occurring in the Ottawa area. The marble sequences of the Grenville series in the Ottawa region are absent. Huge anorthositic intrusions are common and it is rare to find a publication or map not containing some reference to anorthosite. The grade of metamorphism is high, suggesting that these rocks may have been deeply buried. This high grade of metamorphism is one of the reasons for the lively controversy over the Grenville. Many geologists take this to be evidence of fairly old rocks and point out that the K-Ar age determinations which give a relatively young age for the Grenville are not necessarily primary ages, but rather are an indication that these rocks have been involved in more than one orogeny, the latest having taken place about 950 my ago. Recent age determinations, particularly by the Rb-Sr method but by the K-Ar method as well, have shown that the ages are by no means distributed uniformly about a mean age of 950 my. For example, the Rb-Sr measurements of Davis et al (1965) in the Grenville of Ontario indicate apparent primary ages of 1300, 1500, 1700, 2350 my for plutonic rocks in the area. K-Ar measurements in connection with studies of the Brent crater (M.R. Dence, Dominion Observatory, personal communication) give ages of 1500 my for Grenville rocks beneath the crater.

The Grenville Front extends from the shore of Georgian Bay of Lake Huron northeastward to the Labrador coast - roughly a distance of 2000 km. Its trace in Labrador has not been completely defined as regional mapping in the area is just now in its final stages. The location of this boundary given on maps and diagrams in this work has been taken fron the Tectonic Map of the Canadian Shield (1964 edition) compiled by Dr. C.H. Stockwell of the Geological Survey of Canada.

It appears that the Grenville Front is in places a fault, but in others is gradational from high grade metamorphic rocks of the Grenville to the lower grade metamorphics of the other provinces. Various geologists have produced evidence to indicate that in places the Grenville rocks south of the front are more highly metamorphosed equivalents of the rocks in adjacent geological provinces. The best example of this in northern Quebec is the extension of the Labrador Trough rocks into the Grenville. Detailed studies of the extension have been possible because of the presence of the iron formation which is easily identified at all grades of metamorphism. Recent mapping of the extension of the iron formation of the Labrador Trough indicates that south of the Grenville front the gross strike of the formation swings gradually to the southwest and it appears possible that the sequence may cross the Grenville front again east of Lake Mistassini some 250 km to the west of the Labrador Trough.

4-2-5 Summary of Geology.

The Precambrian shield in Canada has been often cited as evidence for the growth of continents by accretion - that is, continents grow as a result of the formation of successive geosynclines on the periphery of the continental mass. In the Canadian shield the evidence for outward growth of continents comes from petrographic, structural and isotopic studies. The K-Ar radiometric data have been a significant factor in support of this concept because the results give a distribution of ages which is consistent with the hypothesis of continental accretion.

This concept of continental accretion as applied to the Canadian Shield is not agreed to by all Precambrian geologists and there are good reasons to question it. K-Ar age determinations for example do not give the primary age of the rock, but rather the age of the last geological event which affected the rocks. Rb-Sr whole rock determinations appear to offer a means of seeing through orogenies and the recent addition of facilities to carry out such measurements at several places throughout Canada will undoubtedly produce more results susceptible to different interpretations than those commonly held at present. The dominance of structural trends more or less parallel to the boundary between adjacent structural provinces also tends to the impression of outward growth. It is open to question whether trends dominant to the extent suggested or implied in some of the literature actually exist. For example, according to Wynne-Edwards the greater part of the Grenville in Quebec is structurally discontinuous; the dominant structural feature being isolated "blobs". A study of the tectonic map of the Canadian shield also indicates that, for example, east-west structural trends are not uniformly present throughout the Superior province. In northern Quebec there are areas where northeast-southwest trending structures or circular, "blob-like" patterns appear to predominate.

As Wynne-Edwards has suggested there appears to be an argument for the idea that the oldest Precambrian rocks formed a platform upon which younger sediments were deposited and through which igneous rocks were intruded and that both the older and the younger rocks were involved in subsequent orogenies. Subsequent long period of erosion then removed all but remnants

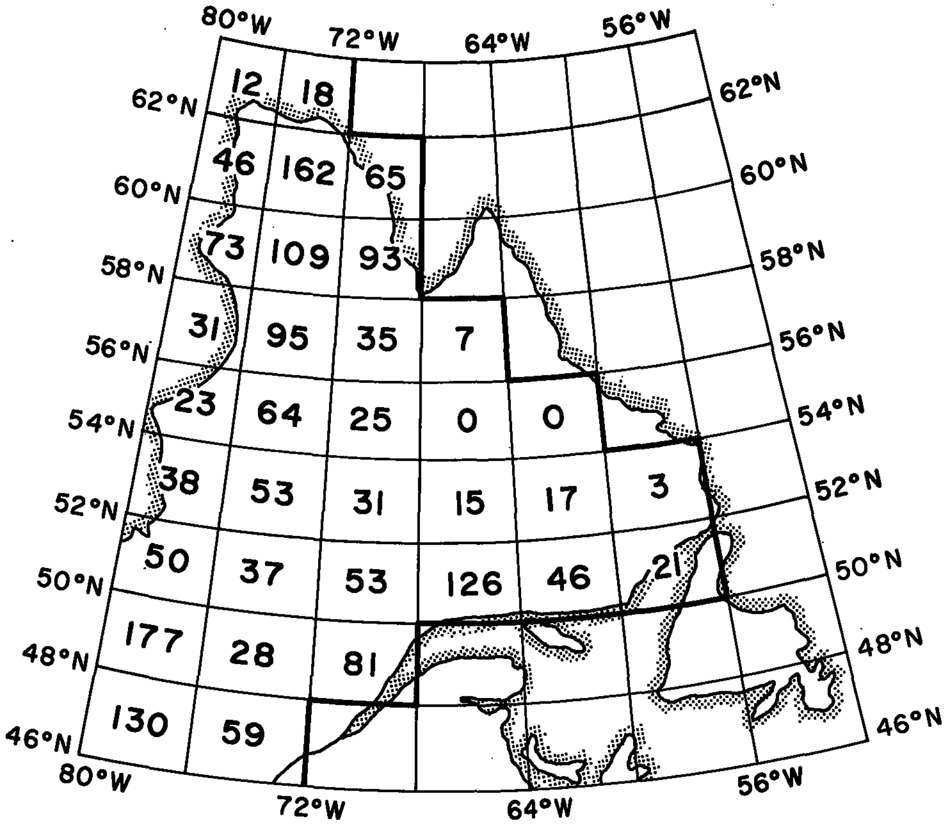


Fig. 4-1

Distribution of rock samples by areas of 2° x 4° in northern Quebec.

of younger overlying rocks in areas such as the Grenville. Broadly speaking there is evidence for the existence of an older platform in other places in the shield. Two such examples are the Slave province in northwestern Canada and Archaean rocks along the cost of Labrador which give about the same K-Ar ages as the Superior province, but which are well removed from the Superior province.

It is important to note that much of northern Quebec is underlain by rocks that are apparently more basic than rocks exposed in shield areas generally. In the Superior province the evidence for a more basic character is solidly based on both surface mapping and geochemical studies. In the Grenville, however, this situation can only be inferred on the basis of the high grade of metamorphism present throughout the province and possibly on the absence of continuous structural patterns in the area lying 250 km or more to the east of Ottawa.

4-3 Density Measurements

Fig. 4-1 shows the distribution of rock samples, for areas of two degrees of latitude by four degrees of longitude, throughout northern Quebec. Although this study is primarily concerned with the area north of 49°N, Precambrian regions south of 49°N have been included for completeness.

The information necessary to compile Fig. 4-1 has been obtained from punched cards prepared from the data gathered during each field program. Contained on each card are such things as station number, location, density, description and a reference to the gravity observation. The cards were processed by computer and the information necessary for Fig. 4-1, as well as Fig. 4-2

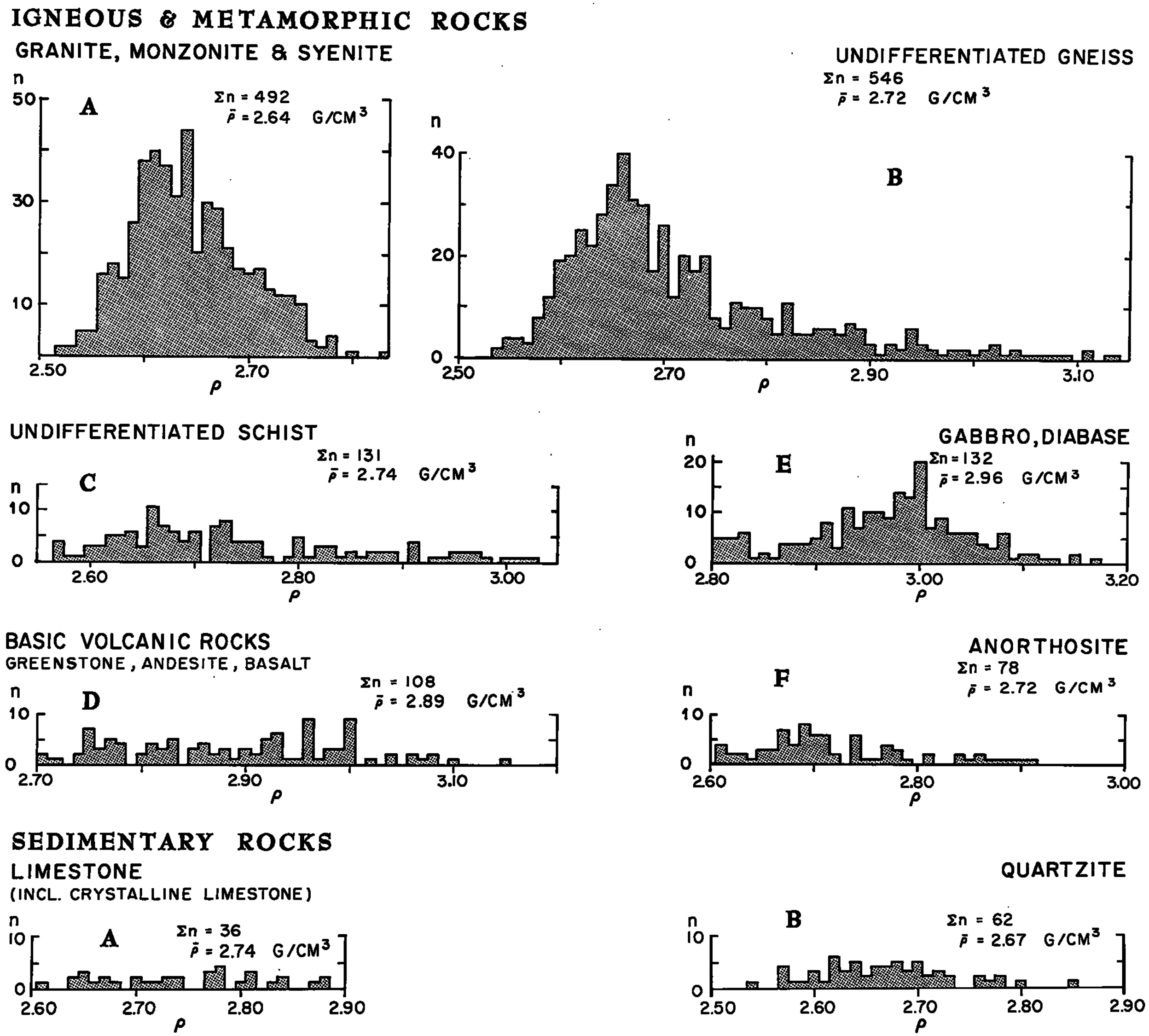


Fig. 4-2 Histograms of rock samples collected in northern Quebec.

discussed subsequently, was provided in printed form. It should be noted that the figures shown in Fig. 4-1 contain data gathered on gravity surveys other than those reported in Chapter 2 as well as data obtained from institutions such as the Geological Survey of Canada. These latter sources constitute about 25% of the total amount of data available.

In Fig. 4-1 two of the areas are indicated as not having been sampled. Rock samples have been collected in the area, but the records have been lost; the work was carried out prior to the adoption of the punched card system andthe results are unfortunately not available.

Fig. 4-2 gives the histograms for the main rock types outcropping in northern Quebec. Although the subdivisions are broad in some cases and the rocks from all areas in northern Quebec are grouped together, a further subdivision, either by area or sub-category, is not warranted because the information available is not sufficient to attach any meaning to such a division. The identifications were carried out by a number of geologists from a study of hand specimens mainly - thin sections were available occasionally - and obviously the familiarity of the particular geologist with the area has been a factor in the identifications. A second factor has been the need to adopt a simplified system of nomenclature suitable for use on computer, which imposed a further limitation on the geologists.

An inspection of Fig. 4-2 indicates that, with possible exception of the granites, there is a large spread in the range of density for any given category of rocks. This is partly a reflection of chemical variations within the rocks of a particular class but is mainly a reflection of the limitations of the system and the ability of geologists to identify the rocks according to the system.

Both the gneisses and granites show pronounced peaks near the acidic end of the "density scale", but there is a rather long tail on the high density end of the histogram for the gneisses. This is probably due to two things: (a) the banding of the gneisses in the Superior province is very coarse and since it is usually easier to break off a chunk of basic rock there has undoubtedly been a tendency on the part of the observers to bias the results toward basic components of the gneiss and, (b) basic gneisses have not been separated from the population.

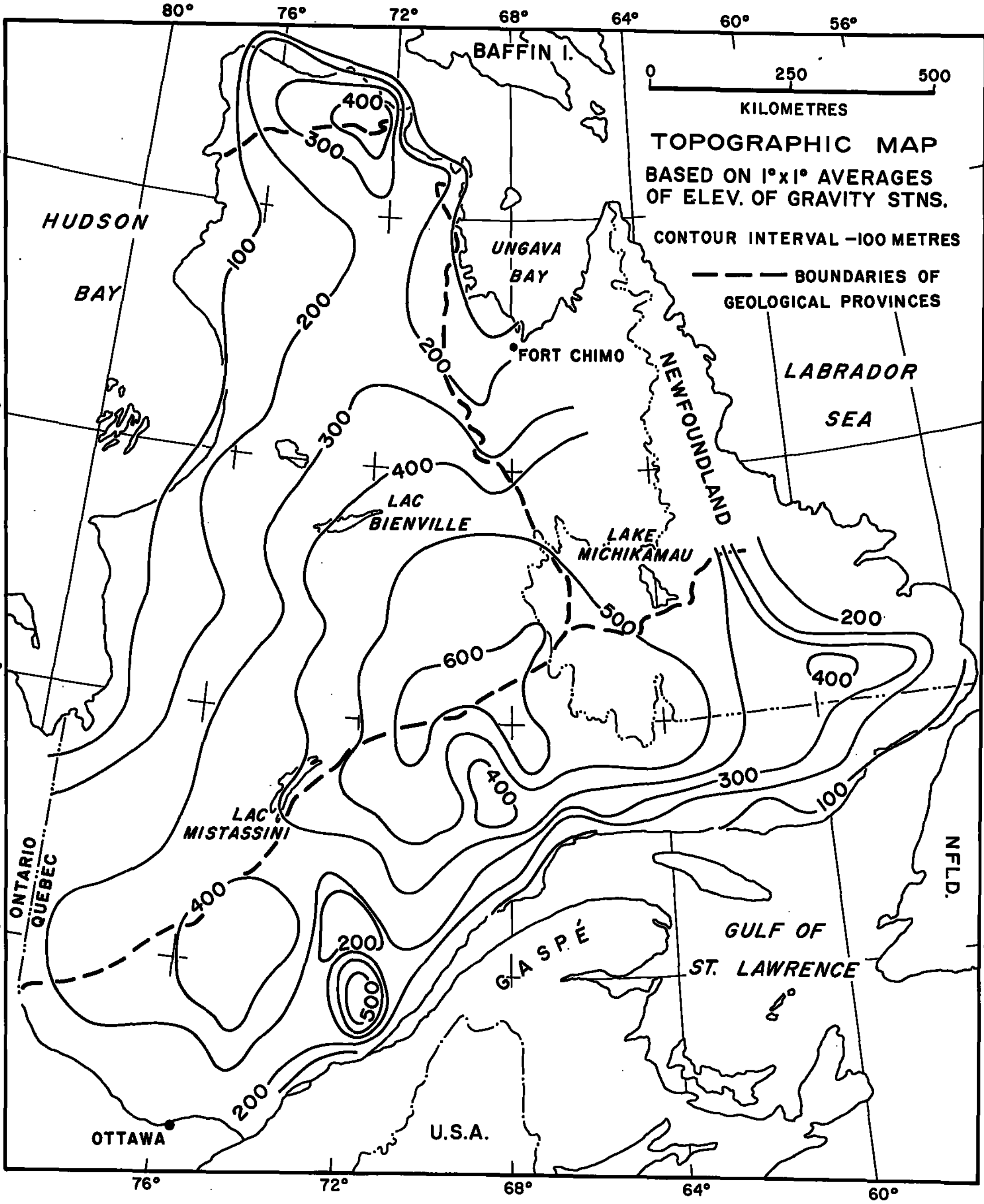
The remainder of the histograms require no particular additional comment except perhaps for that of the anorthosites. Normally samples of pure anorthosite vary little from a density of about 2.7 g/cm^3, but in this case the densities range from about 2.6 g/cm to slightly in excess of 2.9 g/cm . The high densities shown in the histogram can be explained by the presence of varying amounts of ferromagnesian minerals, usually olivine, but the very low densities cannot be as easily explained. Densities less than about 2.65 g/cm^3 are not expected for anorthosites unless the sample is badly weathered. The only other possible explanations for the unusually low densities recorded are weighing errors or misidentifications.

Absent from the histograms in Fig. 4-2 are the granulites. Some samples of granulite were collected and undoubtedly others were collected but identified as another rock type. These rocks are difficult to identify; a problem which was magnified because the areas in which these rocks predominate (mainly the northern part of Superior province) were mapped at a time when geologists working in the area were also in the early phases of their program and the appropriate emphasis had yet to be placed on these rocks. The term granulite is a loose term used to classify rocks formed by metamorphism of existing rocks at very high temperature and pressure. The range of densities expected would be large and it would also be expected that the density of the granulite would be greater than that of the parent rock because of loss of water, alkalis and other low temperature constituents during metamorphism. The change of density due to metamorphism is mainly a function of the temperature and pressure and the composition of the rock, but probably lies in the range 0.05 - 0.20 g/cm^3. This estimate is based on results obtained at the Dominion Observatory (Gibb, 1968) and modal analyses (Dr. G. Holland, Durham University, personal communication).

The average densities shown in Fig 4-2, which will be used as a basis for the interpretation of the gravity anomalies, agree fairly well with those normally adopted in gravity interpretations for these rock types. The main exception is that for the sediments which, in Precambrian areas, are nearly all metamorphosed to some extent. This metamorphism has apparently increased their density because density measurements usually reveal virtually no density difference between the sediments and the gneisses and granites which underlie most Precambrian regions.

4-4. Topography

In Chapter 1 brief reference was made to the nature of the topography in each of the geologic provinces of northern Quebec. In this section the overall form of the topography of all of northern Quebec is of interest for subsequent comparisons with the gravity data. The basis for investigating the form of the



TOPOGRAPHIC MAP
BASED ON 1°x1° AVERAGES
OF ELEV. OF GRAVITY STNS.
CONTOUR INTERVAL -100 METRES
BOUNDARIES OF
GEOLOGICAL PROVINCES
KILOMETRES
0
250
500
BAFFIN I.
HUDSON
BAY
UNGAVA
BAY
FORT CHIMO
NEWFOUNDLAND
LABRADOR
SEA
LAC
BIENVILLE
LAKE
MICHIKAMAU
LAC
MISTASSINI
ONTARIO
QUEBEC
GASPÉ
GULF OF
ST. LAWRENCE
NFLD.
U.S.A.
OTTAWA
80°
76°
72°
68°
64°
60°
56°
52°
48°

Fig. 4-3

topography is the elevations of the gravity stations from which average values by degree squares have been calculated. The map in Fig 4-3 indicates clearly that the broad topographic character is that of a huge asymmetric dome reaching a maximum height of about 600 m above mean sea level over the Grenville Front at approximately 52°N, 70°W. Geologists have stated frequently that shields generally are dome-shaped and as northern Quebec is bounded on three sides at least by major drainage features it is not too surprising that northern Quebec is also dome-shaped.

The distribution of the gravity stations with respect to that of the topography needs some clarification. In all areas but the Grenville the observations were made on lake shores which occupy the lower end of the range of topography. In the Grenville, where helicopters were used, the distribution of gravity stations includes the total range of topography, but there is probably a bias toward the lower end because lake shores provide the easiest means of identifying the locations of the stations and the generally heavy tree cover provides few breaks suitable for landing a helicopter above the general level of the lakes. Since the relief within the Superior province is small and that within the Grenville fairly large it is possible that the position of the apex of the dome should be slightly to the south of that shown in Fig. 4-3. It is also possible that the mean level of the actual topography is higher in the Grenville than that shown in Fig. 4-3.

The reader should retain a mental image of the topography as shown in Fig. 4-3 because reference will be made to it later in this chapter in connection with a brief isostatic study.

4- 5 Summary of Previous Regional Geophysical Studies.

The major contribution to the current geophysical knowledge of northern Quebec has come mainly from gravity studies. The data and information available from gravity investigations have come almost entirely from the work at the Dominion Observatory and, since mubh of the data is included in this study, a summary of the published results will not be given here. Previous interpretations of gravity data will, however, be discussed in the appropriate sections of this interpretation.

Progress with other geophysical studies has undoubtedly been restricted because of the difficulty and expense encountered in gaining access to the region. There have been one or two geophysical programs in northern Quebec that provide useful background for this interpretation of gravity data and there have been programs in adjacent areas of the shield which are also useful in this regard. These will be reviewed briefly in the remainder of this section.

In recent years the Geological Survey of Canada has had a program to provide low-level aeromagnetic data in the southwestern portion of northern Quebec. This data is too restricted in area to have broad application in this study, but will be used in connection with the interpretation of the gravity data over an anorthositic intrusion near the Grenville front.

It is generally accepted that the heat flow values in shield areas are low, although, within the Canadian Shield at least, there are not many measurements. In northern Quebec there is only one reported measurement

(Jessop, 1968) that is relevant to this study. This measurement was made in a drill hole located on Neilson Island in Hudson Bay about 15 km north of Great Whale River. The heat flow is calculated to be 0.59 $\mu cal/cm^2/sec$--less than half the world average. In his analysis of the data Jessop considered possible corrections for climatic history and topography and concluded that these are sufficiently small to indicate that this is a truly low value of heat flow. Jessop suggested that this result in consistent with the results of Eade et al (1966) and Fahrig et al (1967) who postulate that rocks exposed in the area are the product of high grade metamorphism at depth, that the radioactive elements were fractionated during metamorphism, and that subsequent erosion has exposed the present surface by removal of up to 10 km of overlying material.

Jessop (1968) also reported on heat flow measurements near Ottawa and at Halifax. He found that, when a correction for the effect of glaciation is applied, both sites give a value of about 1.35 $\mu cal/cm^2/sec$ which is about 10% below the average world value. He further suggested that heat flow values determined by Meisner et al (1951) and Beck (1963) in southern Ontario and Quebec could also be corrected for the effect of glaciation to become more nearly equal the world average. Since these measurements plus that at Franktown have been made in areas underlain by or containing exposed Grenville rocks, Jessop suggested that the Grenville province might well be removed from the list of low heat flow areas.

The remainder of this section will be devoted to a summary of the crustal seismic experiments and regional P- and S-wave studies of upper mantle structure. There has only been one crustal seismic experiment carried out in northern Quebec and this was carried out during the summer of 1968. Final results of the experiment are not available, but Dr. M.J. Berry of the Dominion Observatory has provided the writer with some preliminary results on the understanding that the tentative nature of the results be stressed.

The 1968 program was designed to study the gross crustal structure in the vicinity of the Grenville front along three profiles parallel to the strike of the gravity anomaly shown on the Bouguer anomaly map in the pocket; this anomaly can also be seen on Figs. 4-5 and 4-6. The profiles were located to the north and south and along the axis of the negative anomaly and were chosen to avoid local anomalies in the gravitational field. The profiles were about 400 km in length with the shot points located at the ends of the profiles. Seismometers were placed at intervals of about 20 km along each profile and cross ties between profiles were obtained at the end points by recording some of the shots along each profile at the ends of the other profiles.

A summary of Berry's preliminary results for each profile is shown in Table 4-2 and attention must be directed toward the unusually high Pn velocities recorded under the northern and southern profiles, which are both about 0.3 km/sec higher than that normally recorded for the upper mantle. The Pn velocity is about normal along the central profile located near the boundary of the Grenville and Superior provinces. The crustal velocities also vary among the profiles, but are of similar magnitude to those recorded in other areas of the Canadian shield (see Table 4-3). Also shown in the table is the range of crustal thickness for each profile obtained from the preliminary analysis.

TABLE 4-2

PRELIMINARY SEISMIC RESULTS - GRENVILLE REGION *

	Northern Profile	Central Profile	Southern Profile
Upper Refractor velocity (km/sec)	6.35	6.44	6.30
Upper Mantle velocity (km/sec)	8.53	8.28	8.64
Crustal Thickness (km)			
Minimum	36	36	38
Maximum	42	50	43

* Dr. M.J. Berry, Personal Communication.

Dr. Berry regards the calculated thicknesses of the crust to be minimum values for the area which probably means that the crustal velocity increases with depth. It is also his opinion that subsequent analyses will not produce any substantial changes of P-wave velocities from those shown in Table 4-2. Since no interpretation of the seismic data has been made, no further comment will be made except to state that these preliminary results will be considered again in the interpretation of the gravity data.

TABLE 4-3

SUMMARY OF SEISMIC RESULTS IN EASTERN CANADIAN SHIELD

	Kirkland Lake[1]	Lake Superior[2]	Hudson Bay[3]	Hudson Bay[4]	Hudson Bay[5]
Upper Refractor velocity (km/sec)	6.25	6.63	6.33	6.35	6.32
Upper mantle velocity (km/sec)	7.91* 8.17	8.10	8.27	8.25	8.23
Crustal Thickness (km)					
minimum	30	27	25	26	26
maximum	40	55	43	41	42

* Based on stations near Kirkland Lake

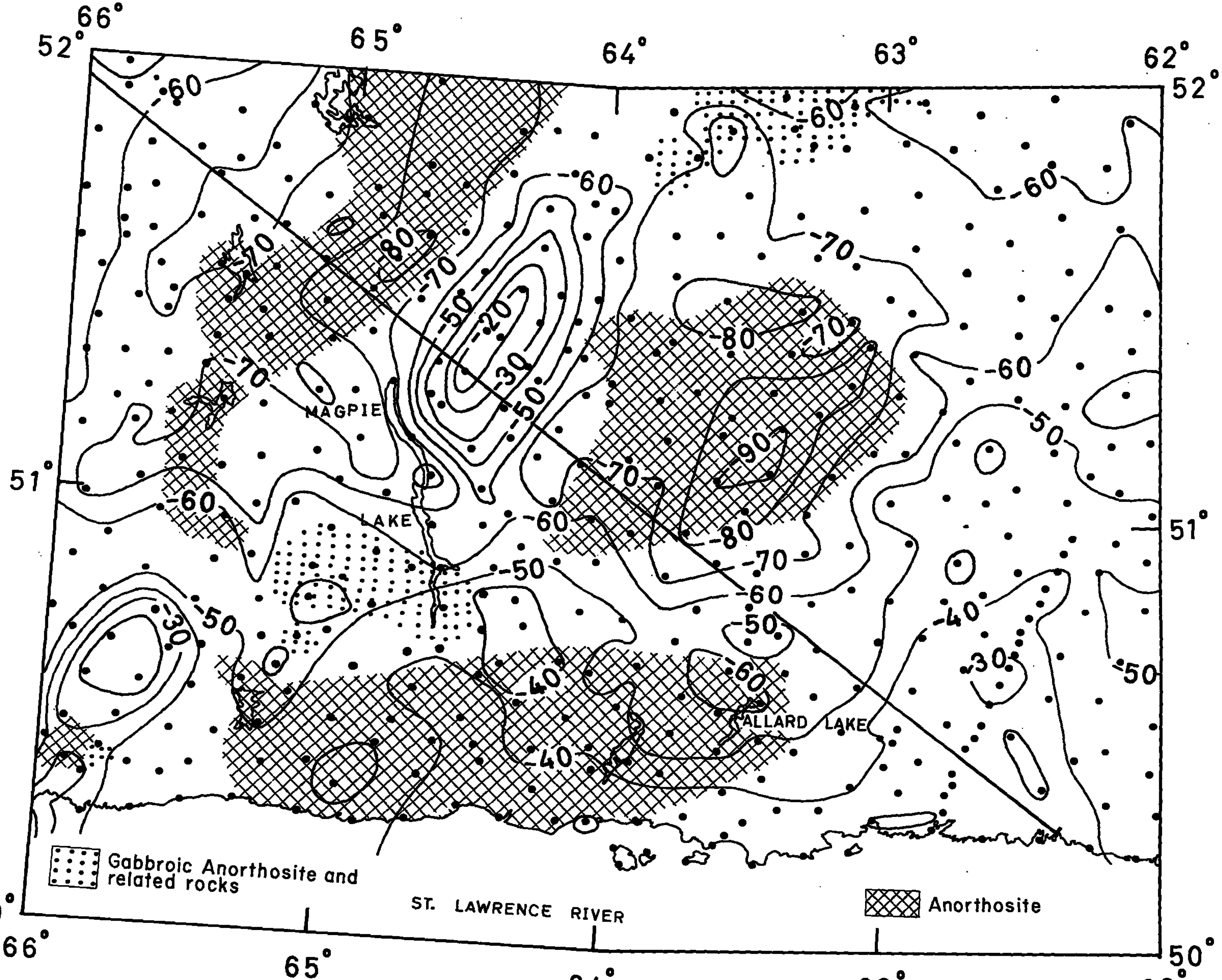
1. Hodgson, 1953
2. Berry and West, 1967
3. Ruffman and Keen, 1967
4. Hobson et al, 1967
5. Hunter and Mereu, 1967

Table 4-3 gives a summary of other seismic results in the eastern Canadian Shield. The Hudson Bay and the Lake Superior experiments involved several agencies each of whom carried out a separate interpretation of all the data. Only one result is given here for Lake Superior but it should be pointed out that other interpretations of the data exist (c.f., Smith, Steinhart and Aldrich, 1966). The solutions to the data in both the Lake Superior and Hudson Bay regions were obtained by the time-term method (Scheidigger and Willmore, 1957), although both experiments were laid out in the form of profiles.

Tables 4-2 and 4-3 indicate that the crustal thickness is quite variable and, indeed, variations of the magnitudes shown in the tables should produce gravity anomalies of the order of hundreds of milligals in some instances. Such anomalies are simply not observed in these areas, which suggests that time-term variations might be explained on the basis of lateral changes of P-wave velocity in the crust and upper mantle rather than by changes of crustal thickness exclusively. In this connection Ruffman and Keen (1967) estimate that the Mohorovicic profile could be smoothed by either allowing crustal velocities to vary laterally between 6.14 and 6.55 km/sec or allowing the velocity of upper mantle to vary between 8.24 and 8.34 km/sec. These ranges are both plausible.

Weber and Goodacre (1968) investigated various ways of reconciling the seismic and gravity data in Hudson Bay. They found a variety of models that were generally consistent with both sets of data, but concluded that there is insufficient data available with respect to variations of P-wave velocities and crustal densities and their functional relationship, if any, to draw any firm conclusions about the area.

The other interesting aspect of the seismic studies in the eastern Canadian shield is the lack of any basic evidence to suggest the presence



66°
65°
64°
63°
62°
52°
51°
50°
-60
-70
-80
-50
-20
-30
-90
-40
MAGPIE
LAKE
ALLARD LAKE
Gabbroic Anorthosite and related rocks
ST. LAWRENCE RIVER
Anorthosite
SCALE
0
20
40
KILOMETRES

MAGPIE

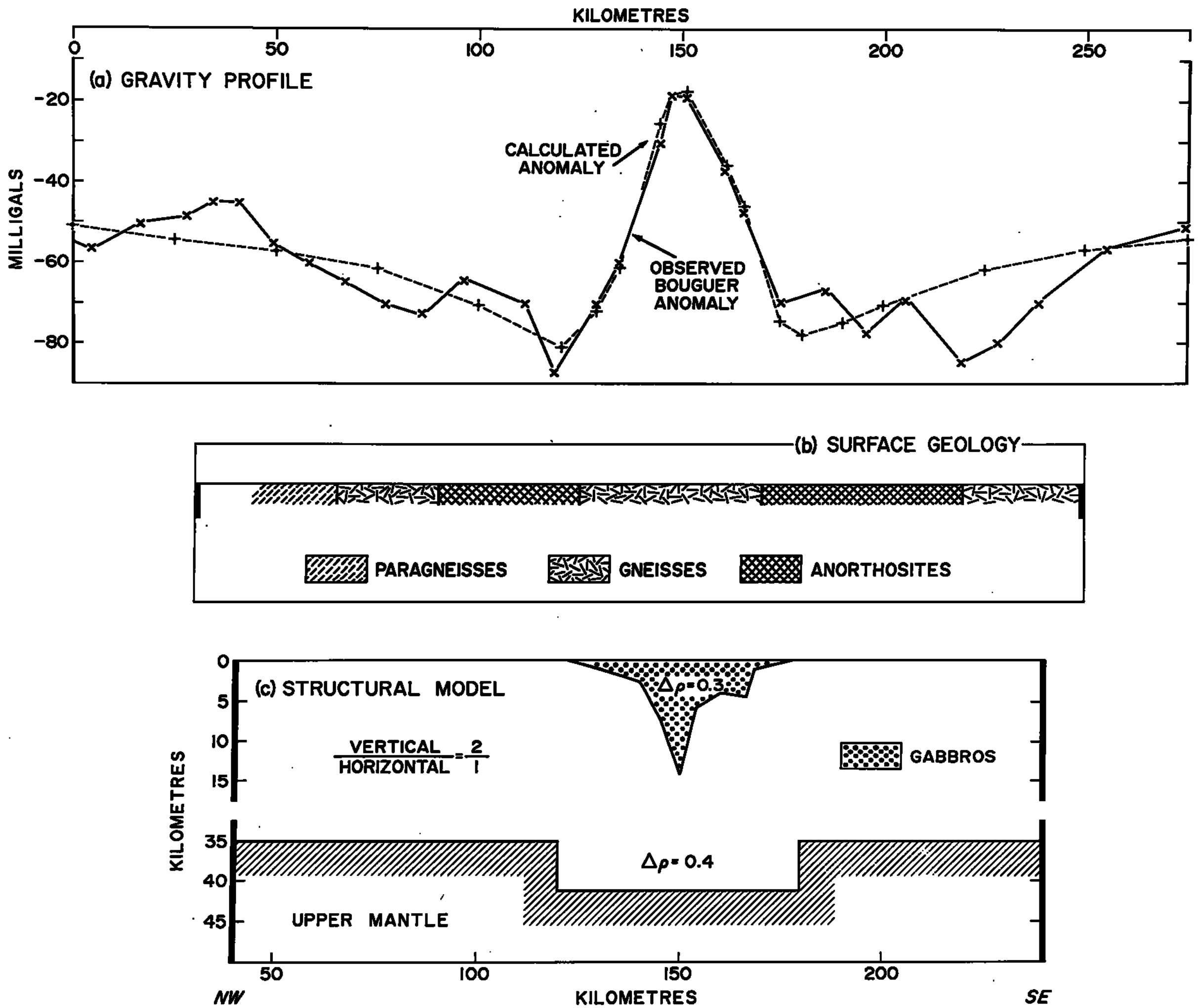
anorthosite. The contacts between the granites and the host rocks are gradational. The apparent youngest rocks in the region are a series of basalt dikes. Structurally the area is complex with the main trend being a pronounced westward dip which gives the impression that the area is underlain by a huge sill.

The main features of the gravity map (Fig. 6-4) are the large positive anomaly east of Magpie Lake and the regionally depressed field in the area surrounding the Magpie anomaly. Correlation of the distribution of intrusive rocks with the gravity field indicates that centres of minimum anomaly are located over anorthosite masses to the northwest and southeast of the Magpie anomaly.

Although basic rocks are not shown to outcrop within the limits of the Magpie anomaly, there does not seem much doubt from the available information, sketchy though it is, that the anomaly is causdd by a large volume of basic rock. The few samples collected by the author in 1965 gave densities of about 3.0 g/cm^3. The work of Rose, mentioned earlier, on the huge iron ore deposit located on the northeastern margin of the gravity anomaly indicated that basic rocks are present and suggested the existence of a large basin-shaped structure to the west.

The Bouguer anomaly field is shown along a northwest-southeast profile in Fig. 6-5. From north to south the anomaly gradually decreases in an irregular fashion for a distance of about 125 km to a minimum value of about

Fig. 6-5 Interpretation of gravity anomalies in the Magpie Lake area.



-80 mgal just north of the Magpie area. The Magpie anomaly in the middle of the profile is about 50 km wide and reaches a maximum anomaly of about -20 mgal. Immediately, south of the Magpie anomaly the Bouguer anomaly is regionally low and then gradually and irregularly rises to a value of about -50 mgal at the southern limit of the profile.

The cause of the regionally low gravity values and the shape of the regional trend are difficult to decide upon because the gravity field is irregular. In this study the Bouguer field will be separated and interpreted as follows:

(a) a regionally negative anomaly due to a thicker crust which compensates for the high density rocks causing the Magpie anomaly,

(b) the Magpie anomaly which is caused by basic intrusive rocks,

(c) local anomalies in the area surrounding the Magpie anomaly which are assumed to be caused either by the anorthosites or by local phases within the anorthosites.

The local anomalies (c) are not interpreted quantitatively.

The alternative to assuming the crust is locally thick under the Magpie intrusion would require that low density rocks, probably intrusive, occur over a width of some 200 km along the profile. For a regional anomaly with an amplitude of about 40 mgal and for an assumed density contrast of -0.1 g/cm^3 the thickness of low density crustal rocks would be about 10 km. If this low density material represents a marginal phase of the basic intrusion then its dimensions exceed by far those of any suggested marginal phase reported in the literature.

Since the contacts of the basic intrusion assumed to cause the Magpie anomaly are not known, their dip cannot be established conclusively. However, it would seem likely that they dip inwards. The gravity profile in Fig. 6-5 displays very steep gradients along the margins of the anomaly and also rises to a very sharp peak. This contrasts sharply with anomalies caused by anomalous masses with outward sloping contacts such as the Weardale granite (Fig. 3-4) which usually have gentle gradients on the margins and a flat top. Rose, as mentioned previously, has suggested that there is a huge basin structure underlying the anomaly. It is concluded from this evidence that the contacts of the basic intrusion dip inwards.

The structural model in Fig. 6-5 shows a basic intrusion up to 15 km thick compensated by a 7 km increase in crustal thickness. The observed and computed profiles agree excellently over the Magpie intrusion. It is harder to judge the appropriateness of the regional curve because of the existence of numerous local anomalies which cannot be interpreted from the information available. However, it does appear to explain the gross regional trend.

The gravity interpretation of the Magpie anomaly is similar to that of the Pletipi anomaly in that both anomalies can be interpreted in terms of compensated structures. The major difference between the two interpretations is the depth at which the compensating mass can be placed. It is unfortunate that there is insufficient information to be more definite about the interpretation

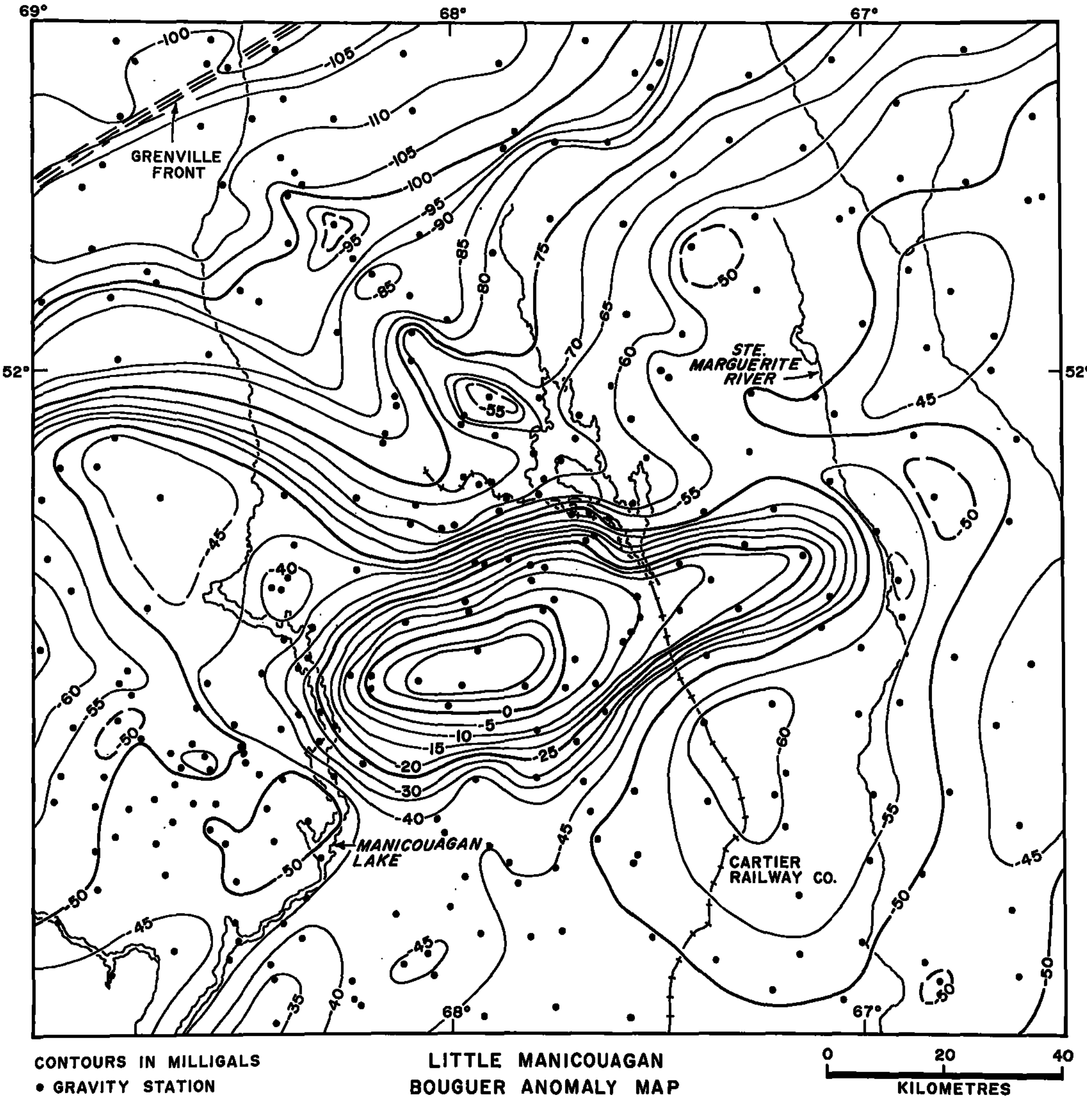


Fig. 6-6

Gravity map of the Manicouagan Lake Area. Location of the Grenville Front is after Stockwell (1965). Gravity units are milligals.

because comparison of these two anomalies could lead to a better understanding of the mechanism of compensation and the level at which compensation takes place.

In this interpretation the thickness of the crust is assumed to be 35 km. Calculations made assuming a crust 40 km thick (not shown) provide an equally good fit to the assumed regional anomaly.

The contacts of the basic intrusion shown in Fig. 6-5 were determined on the basis of results from the Sedimentary Basins program. This was achieved by placing blocks, 5 km wide, from one edge of the local anomaly to the other. Blocks on the margins which are not needed are set to zero thickness by the program. Since these intrusions stand out topographically, a test of the computer results can be made by comparing the calculated position of the contact to the topography. In the Magpie area this comparison indicates that the positions of the contacts shown in Fig. 6-5 are reasonable.

6-4. The Manicouagan Intrusion.

The gravity anomaly over this intrusion (Fig. 6-6) has in plan view the general shape of a huge crescent. The highest anomalies within this crescent are found to the east of Manicouagan Lake. The maximum Bouguer anomaly in the area is about 15 mgal at a point just east of Manicouagan Lake. The area of very high Bouguer anomaly is about 100 by 40 or 50 km, but the total area of the crescent is about twice this figure.

Like the previous interpretations, this is hampered by the lack of adequate geological mapping and it will be necessary to proceed on the basis of

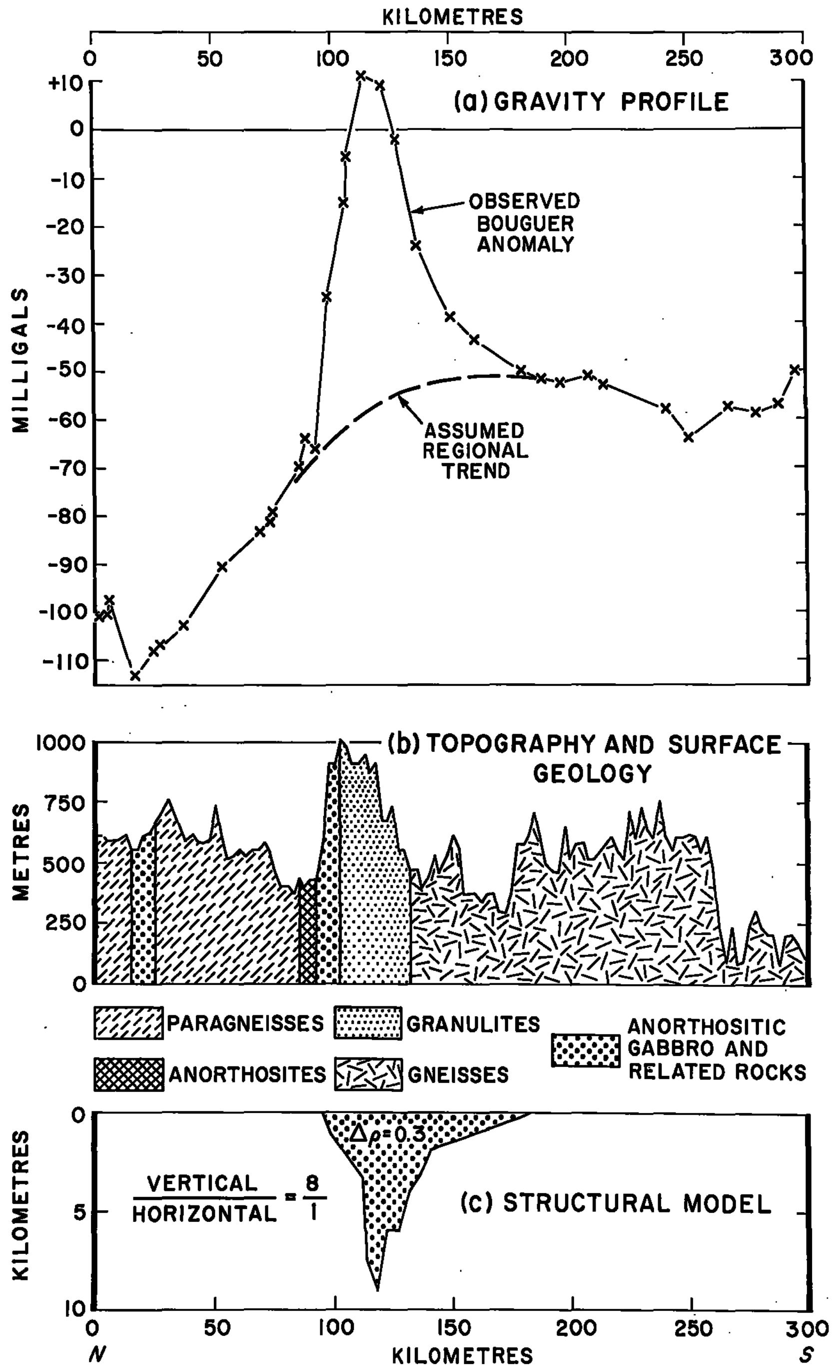


Fig. 6-7

Interpretation of the Manicouagan gravity high.

observations carried out at the Observatory. These consist of scattered rock samples in the area west of the Quebec Cartier Railway (Fig. 6-6). The results of this work agree substantially with the surface geology shown in Fig. (6-7). Intrusive rock outcrops mainly along a prominent range of hills which marks approximately the northern edge of the intrusion. The rocks in this area are mainly anorthositic gabbros, but anorthosite does occur locally and in scattered regions to the south of this range of hills. South of the hills the rocks are variable, but consist mainly of highly altered gnesisses (granulites). The occasional outcrop of coarsely grained granitic rocks can be found, but there does not seem to be any extensive occurrence of these rocks.

The topographic relief over the intrusion (Fig. 6-7) is perhaps the most spectacular of any of the intrusions considered. The range of hills which roughly mark the north boundary of the intrusion, rise steeply from a small comparatively flat plain to the north. The highest peaks are found in the most northerly part, but peaks reaching heights of about 900 m are found for some 30 km to the south.

Relief of this magnitude raises a question with regard to errors in the Bouguer reduction due to the assumptions of uniform density and negligible terrain correction. The assumption of uniform density works well in areas where the terrain is fairly flat because departures from the assumed density can be taken into account in the interpretation. In areas where the relief is substantial this is no longer true and the Bouguer anomalies will be in error by an amount proportional to the magnitude of the relief and the difference between assumed and actual densities.

In this area the crustal density assumed over the intrusion is too low and the calculated Bouguer anomalies would be relatively too high. For a density contrast of 0.3 g/cm^3 and a change of elevation equal to about 500 m the relative error in the Bouguer anomaly can be estimated at 6-7 mgal. Application of the terrain effect increases the Bouguer anomaly and would tend to cancel the error made in the density assumption used to calculate the Bouguer anomaly.

The regional gravity field does not show any strong evidence for local compensation of the mass of the intrusion, but it is noted that the Grenville low is about 10 mgal more negative than shown in Fig. 5-10. There is also a negative anomaly of small amplitude to the south of the Manicouagan high. These observations might be interpreted as evidence for compensation, but, since the interpretation would involve the Grenville anomaly, the problem is too complex to attempt without added information.

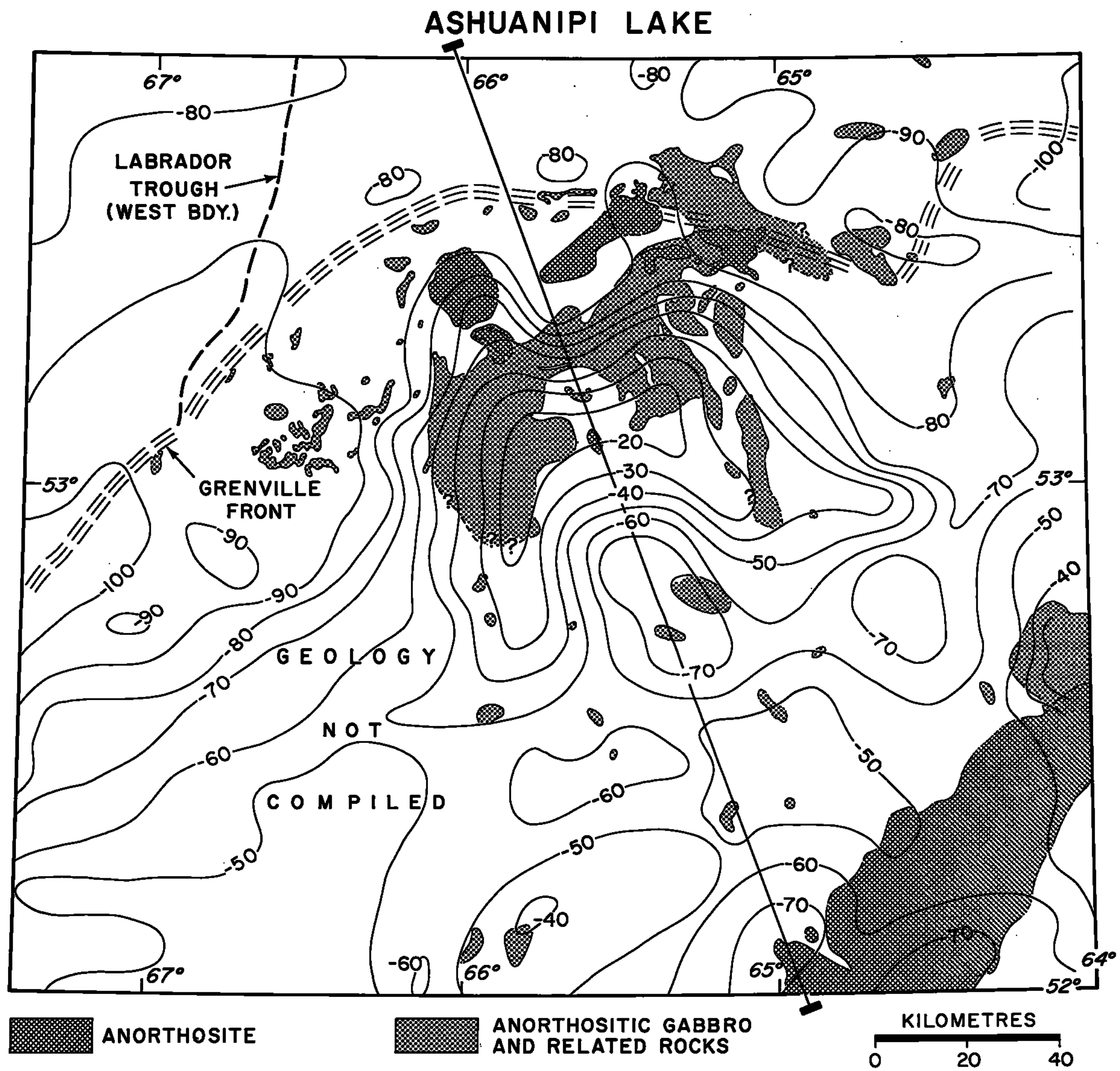
The computed model is shown in the bottom of Fig. 6-7 and the maximum thickness of the intrusion is about 10 km. The contacts, which have been established from the output of the sedimentary basins program, are inward dipping. The relationship of gravity and geology at the northern margin of the anomaly confirm this result for the northern contact. The southern contact could be slightly domed, but the steep gradients would appear to require that the major attitude of the contact be inward dipping.

6-5. The Ashuanipi Intrusion.

This is the third of four intrusions which lie more or less in a line just south of the Grenville Front and parallel to it. It also lies on the extension of the

Fig. 6-8

Gravity map of the Ashuanipi Lake Area. Distribution of intrusive rocks shown on map is after Fahrigh (1960), Wynne-Edwards (1961), Stevenson (1962) and Jackson (personal communication). The gravity units are milligals.



ASHUANIPI LAKE
LABRADOR TROUGH (WEST BDY.)
GRENVILLE FRONT
GEOLOGY NOT COMPILED
67°
66°
65°
64°
53°
52°
ANORTHOSITE
ANORTHOSITIC GABBRO AND RELATED ROCKS
KILOMETRES
0
20
40

Labrador Trough (Fig. 6-8) into the Grenville province and is undoubtedly a major factor in the metamorphism of the equivalent of the Labrador Trough rocks in the Grenville. Preliminary geological mapping in reconnaissance form is available for the area, which is fortunate because the work by the Observatory produced few rock samples. No supplementary gravity observations have been made in the area.

A generalized distribution of the anorthosites and anorthositic gabbros is shown in Fig. 6-8 along with a Bouguer anomaly map for the region. Geological work in the area has been carried out by Fahrig (1960), Wynne-Edwards (1961) and Stevenson (1962). In addition Dr. G. Jackson of the Geological Survey of Canada, who has worked in the area to the southwest of the Ashuanipi gravity anomaly, provided some unpublished preliminary results which have been included in Fig. 6-8. Since the greatest area of outcrop of basic intrusive rocks lies within the area mapped by Wynne-Edwards, his description will be used here.

The gravity anomaly, which in plan view has crudely the shape of an ox-bow, is underlain by an extensive outcrop of intrusive rocks along its northern margin only. The remainder of the area is underlain by gneisses and paragneisses (some of which may be highly metamorphosed equivalents of Labrador Trough strata) and scattered occurrences of basic intrusive rock. The bulk of the intrusive rocks is apparently a diabasic gabbro, but other rocks such as troctolites and anorthositic norite which fall into the general category of anorthositic gabbros also occur. The areas shown on Fig. 6-8 as anorthosite are

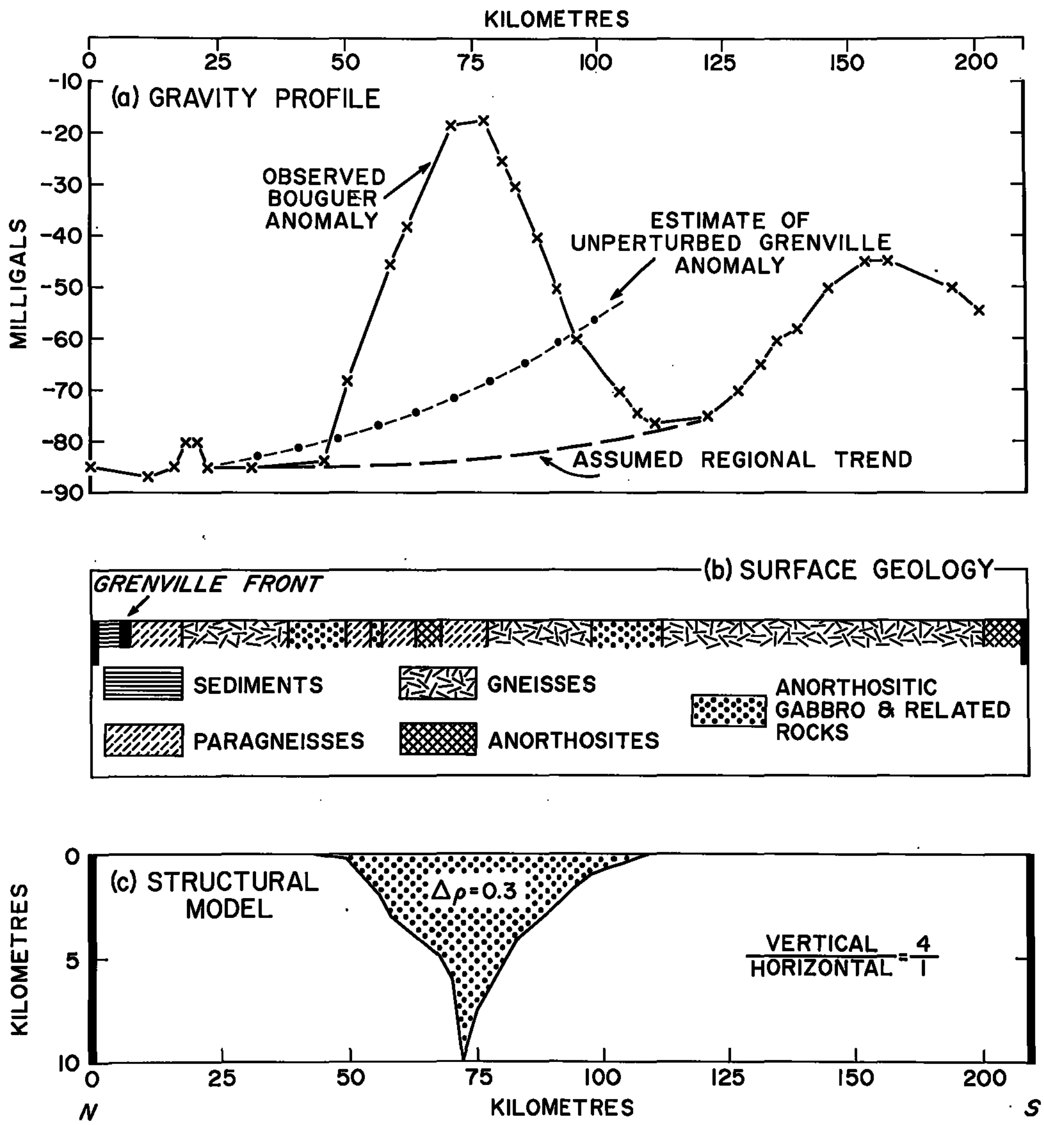


Fig. 6-9

Interpretation of the Ashuanipi gravity high.

apparently very coarsely grained and contain a significant amount of basic constituents. The outcrops of basic intrusive rock are massive and give the impression of a very large intrusion which is in contrast to the basic intrusions in the Labrador Trough (not shown on Fig. 6-8) which are small and sill-like. This difference has led Wynne-Edwards to suggest that the two sets of intrusions are of different age.

As unusual feature of the Bouguer anomaly map is the presence of a locally negative anomaly in the centre of the ox-bow-shaped positive anomaly. Since the gradients are steep, a marginal acidic phase of the intrusion may be indicated. However, this conflicts with the geological data as Stephenson (1967) reports the presence of basic and ultrabasic rocks in this area.

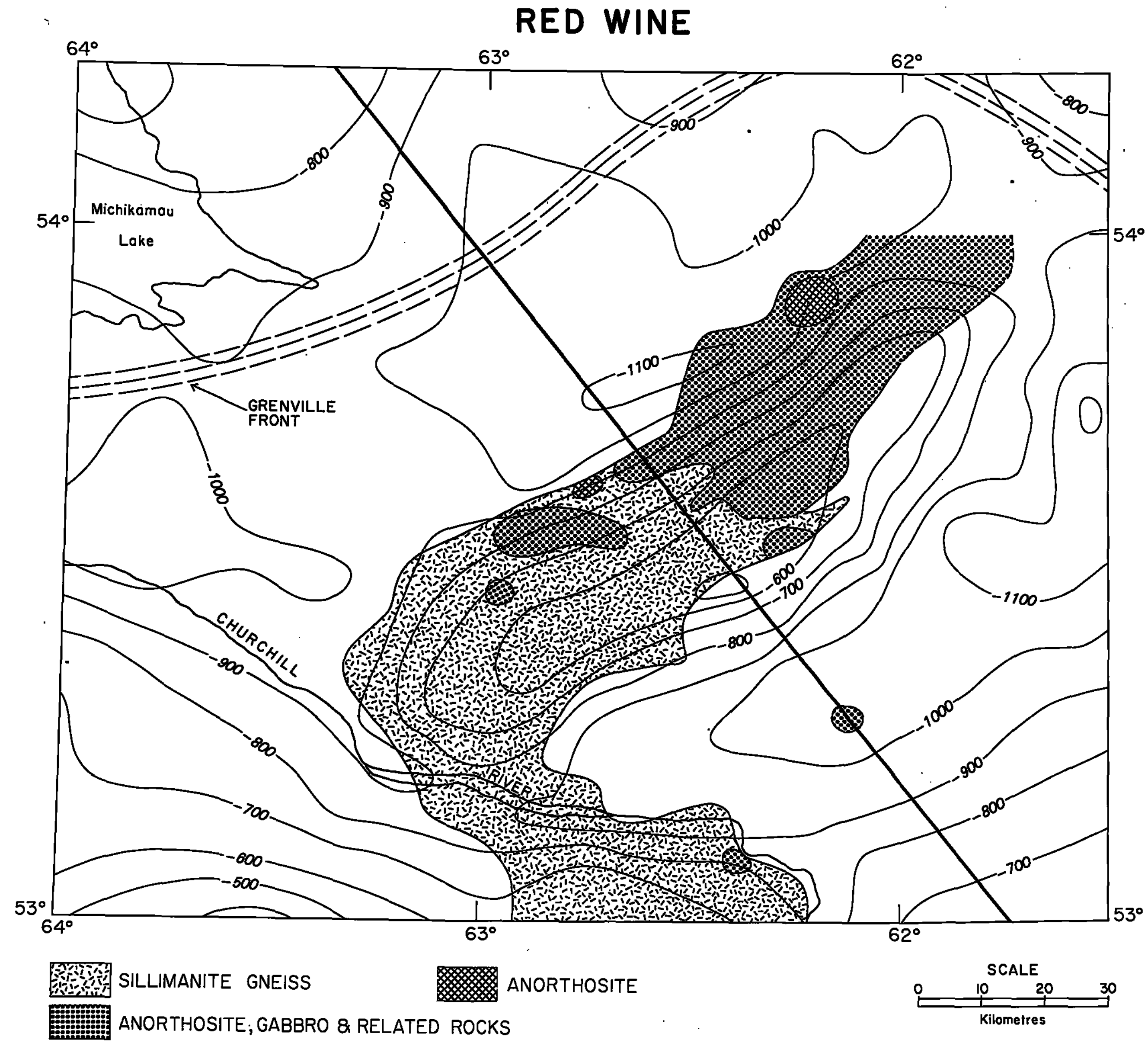
The Bouguer anomaly is shown in Fig. 6-9 along a profile that has been assembled from the regional gravity stations supplemented by use of the gravity contours. These latter have been mainly used as a guide to interpolating between observations on either side of the profile. Correlation of gravity and surface geology leaves little doubt that the northern contact of the intrusion dips southward at a shallow angle. It would appear similarly so for the southern contact. The interpretation of this anomaly is complicated by the presence of the Grenville low immediately to the north and the presence of the negative anomaly to the south of the Ashuanipi high. The interpretation has been simplified by assuming the regional trend shown in Fig. 6-9. The contacts of the intrusion were first defined by the sedimentary basin program and then compared with those indicated by geological mapping. Agreement between the two was excellent and only minor changes were required to compute the model shown.

The source of the local negative anomaly is a problem which can only be outlined here because of the complexity of the problem and the lack of adequate information. Part of the problem lies with the uncertainty about the relationship of the Grenville low and the Ashuanipi gravity high. An estimate of the Grenville low, based on the trends to the east and west of the Ashuanipi gravity high, is shown in the gravity profile of Fig. 6-9. If this estimate is approximately correct then there is a negative anomaly in excess of 20 mgal associated with the gravity high. This could be readily interpreted as being caused by a large marginal granitic phase of the basic intrusion if it were not for the presence at the surface of gabbroic rock. This gabbroic rock could, of course, be regarded as a thin layer exposed at the surface which is underlain by granitic rocks.

There is at least one alternative to interpreting the granites as the source of the negative anomaly. This comes about by relating the steep gradients of the southern limb of the negative anomaly to a local positive anomaly caused by a gabbroic intrusion to the south. The negative anomaly could then be treated as a regional rather than a local anomaly which could be caused by a structure at depth, perhaps even at the base of the crust. Fig. 6-8 does not indicate the presence of an unusual amount of basic rock in the southern part of the profile nor does it indicate the maximum value of the anomaly is unusually high for the Grenville. In the absence of stronger evidence this interpretation is, like that for a marginal granitic phase, speculative.

Fig. 6-10

Gravity map of the Red Wine Mountains area. Geology is after Stevenson (1969, in press). Note that the gravity units are 0.1 mgal.


RED WINE
64°
63°
62°
54°
53°
Michikamau Lake
GRENVILLE FRONT
CHURCHILL
RIVER
800
900
1000
1100
600
700
500
SILLIMANITE GNEISS
ANORTHOSITE
ANORTHOSITE, GABBRO & RELATED ROCKS
SCALE
0
10
20
30
Kilometres

6-6. The Red Wine Intrusion.

This intrusion like the Pletipi intrusion lies within the Grenville low. The associated gravity anomaly, which covers an area roughly 100 by 50 km and rises some 50-60 mgal above the level of anomaly in adjacent areas, is shown in Fig. 6-10 with the geology relevant to the immediate area of the Red Wine Mountains. The surface geology, which is based on the work of Stevenson (1969, in press), clearly suggests that the gravity high is related to anorthositic gabbroic rocks underlying the northeastern portion of the anomaly. These basic rocks are succeeded to the southwest by sillimanite schists, probably of sedimentary origin, which appear on the map as a continuation of the basic rocks. The high gravity anomalies over these rocks suggest that they may be genetically related to the basic intrusive rocks. These sillimanite schists extend to the south of the gravity anomaly and beyond the limits of the map. Occasional outcrops of basic intrusive rock, which Stevenson has shown as equivalent to the main massif, occur throughout the area underlain primarily by sillimanite schists. Stevenson suggests that these are small plugs.

The rocks immediately adjacent to the basic intrusive rocks and the sillimanite schists are mainly gneisses (Fig. 6-11). The gneisses vary from acidic to basic in composition and are intruded by pegmatite dykes. The northeast portion of the map area is underlain by a large area of granites whose relationship to the other rocks of the area is not known. These rocks are coarsely grained and are only slightly metamorphosed. Further to the northeast, on the east shore of Lake Michikamau, there is another huge anorthositic intrusion (Emslie, 1965).

The Red Wine gravity high is shown in the profile in Fig. 6-11. It lies in a trough of low gravity anomalies which undoubtedly represent the extension of the Grenville low into the area. The interpretation of the Grenville low in this area has not been attempted because of the lack of data. The complexity of the interpretation is perhaps greater here than in the area west of the Labrador Trough because of the presence of granites in the area and possible influences exerted by the intrusion of the Red Wine massif on the development of crustal structure. The effect of the granites on the gravity field in the area may not be large because there is no clear evidence to suggest they intrude the country rocks. They may even represent local granitized phases in the country rock. One other possible factor that may be important in the interpretation of the Grenville low is the relationship of the Grenville province to the Nain province to the north. This latter province has apparently undergone a history similar to that of the Grenville except that the major orogeny is believed to have taken place about 1250 my ago (Stockwell, 1965).

The local anomaly due to the Red Wine intrusion has been defined by assuming the regional trend indicated on the diagram. On this basis the anomaly has an amplitude of about 80 mgal. Since the location of the profile was chosen prior to the completion of geological mapping in the area, it is unfortunately located just to the southwest of the main area of outcrop of the anorthositic gabbros. However, comparison of the limits of outcrop of the anorthositic gabbros and the sillimanite gneisses with the limits of the gravity

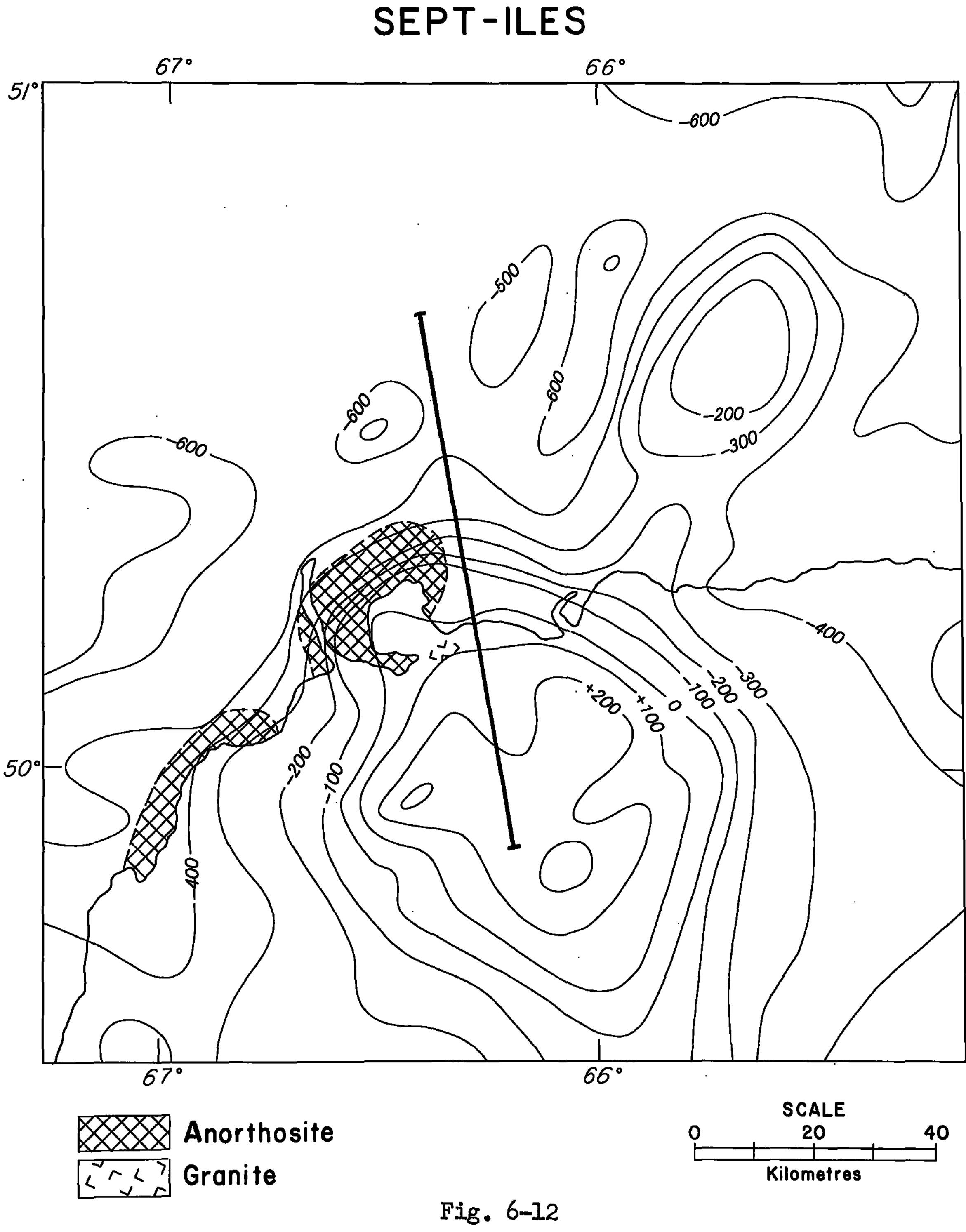


Fig. 6-12

The gravity map of the Sept Iles area. Gravity data in the Gulf of St. Lawrence is after Goodacre, Brulé and Cooper (1969). Geology is after Faessler (1934). Note that the gravity units are 0.1 mgal.

anomaly suggests that the contacts must dip steeply inward. The Sedimentary Basins program could not produce a model with the contacts located as shown in the profile that was in good agreement with the observed anomaly along its margins. This could mean that the assumed regional is incorrect or that the upper surface of the intrusion is lightly dome-shaped rather than flat as shown in Fig. 6-11. This doming, however, could not be the dominant structural form of the intrusion because the horizontal gradients observed on the flanks of the anomaly could not be satisfied by such a structure.

The computed model at the bottom of Fig. 6-11 has the unusual feature of a vertical face over 10 km in height in the southern part of the intrusion. This could indicate the presence of a fault which provided the avenue for intrusion.

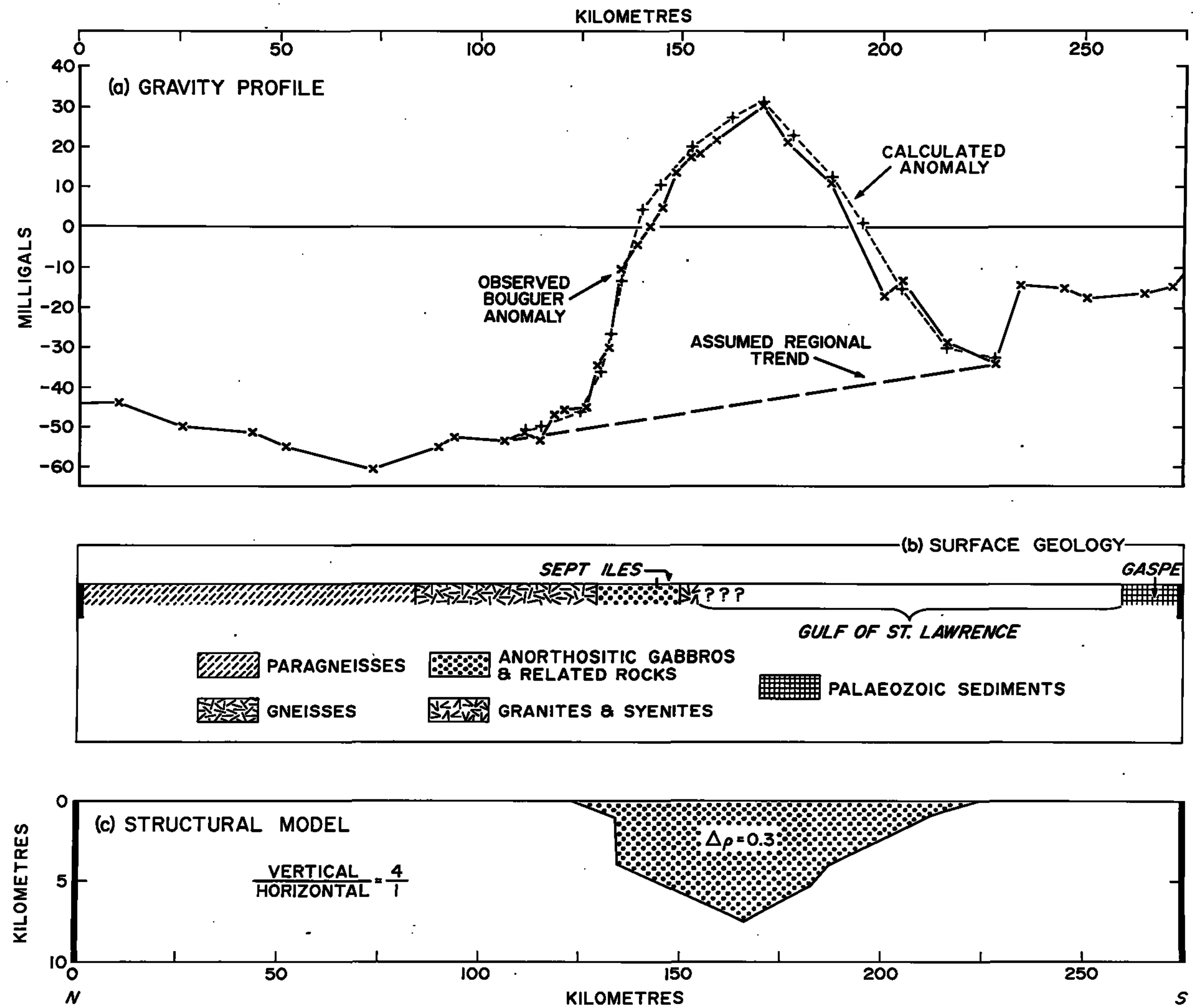
The Red Wine anomaly is the only one of the six local anomalies studied here for which the sedimentary basins program could not produce a reasonable model at a density contrast of 0.2 g/cm^3.

6-7. The Sept Iles Intrusion.

The existence of this gravity anomaly has been known since 1954, but it was not until the underwater gravity measurements in the Gulf of St. Lawrence were completed (Goodacre, Brulé and Cooper, 1969, in press) that its horizontal extent became known. This intrusion is, according to the gravity data (Fig. 6-12), the largest of all the intrusions and, from the geology (Fig. 5-9), may be part of a complex of anorthosites and anorthositic gabbro which outcrops over a considerable length of the northern shore of the Gulf of St. Lawrence.

Fig. 6-13

Interpretation of the Sept Iles gravity high.



KILOMETRES
0
50
100
150
200
250
40
30
20
10
0
-10
-20
-30
-40
-50
-60
MILLIGALS
(a) GRAVITY PROFILE
CALCULATED ANOMALY
OBSERVED BOUGUER ANOMALY
ASSUMED REGIONAL TREND
(b) SURFACE GEOLOGY
SEPT ILES
???
GASPE
GULF OF ST. LAWRENCE
PARAGNEISSES
ANORTHOSITIC GABBROS & RELATED ROCKS
PALAEOZOIC SEDIMENTS
GNEISSES
GRANITES & SYENITES
(c) STRUCTURAL MODEL
$\Delta\rho = 0.3$
VERTICAL / HORIZONTAL = 4 / 1
KILOMETRES
0
5
10
N
S

Since the gravity data show the Sept Iles area to be the centre of maximum anomaly, it is possible that the main feeder for the zone of intrusive rock lay in this area with subsidiary feeders lying along a line extending to the east and west of the area.

The geology of the Sept Iles region has been mapped by Faessler (1942). In recent years the Quebec Department of Mines has also sponsored graduate students but the results are not available. The Sept Iles massif consists of intermixed anorthosite and gabbro which grade from one to the other without sharp contact. Huge plagioclase crystals measuring several feet in diameter are well developed throughout the area. The intrusive rock is very massive and is apparently neither banded nor schistose. The anorthositic rocks are associated with younger granitic rocks which outcrop on the islands south of the city of Sept Iles. Faessler suggests that these granites are acidic phases which probably developed in the late stages in the crystallization of the magma. The youngest rocks in the area are diabase which cut both the intrusive and the country rocks.

The gravity profile shown in Fig. 6-13 extends from the Grenville province north of Sept Iles across the Gulf of St. Lawrence into the Gaspé Peninsula. The positive anomaly over the Sept Iles intrusion contains several local anomalies which are probably caused by late stage granitic rocks associated with the basic intrusion. These are not interpreted, but the small amplitude of the local anomalies suggests that these granitic rocks are thin.

There is a broad area of low Bouguer anomaly north of the Sept Iles gravity high. The surface geology in this area consists of paragneisses and granitic gneisses common to many parts of the Grenville province and these rocks would not be expected to produce low gravity values. It is possible that the low gravity values are caused by a buried structure.

On the assumption that the regional trend is linear the Sept Iles gravity high has a maximum amplitude of 75 mgal. The northern contact of the intrusion is located near the northern margin of the gravity anomaly which indicates that this contact must dip inwards. It is assumed that the southern contact, located beneath the Gulf of St. Lawrence, also dips inward. The structural model shown in Fig. 6-13 is more block-like than those of the other intrusions interpreted in this chapter. The maximum thickness, assuming a density contrast of 0.3 g/cm^3, is about 7 km.

6-8 Summary and Discussion of Interpretation of Local Anomalies

This preliminary interpretation of the anorthositic intrusions has demonstrated the complexity of the Grenville province. The main problem is the cause of the negative anomalies associated with the positive anomalies over the intrusions. In two areas, Pletipi Lake and Magpie Lake, there are fairly well defined negative anomalies that could be ascribed to sources at depth and therefore can be interpreted as compensation, by warping or collapse, for the basic intrusive rock. In the Pletipi interpretation warping must take place along an intermediate layer and the validity of this interpretation is in doubt because of the lack of evidence for an intermediate layer in the eastern Canadian Shield. In neither case is the geological information adequate to exclude definitely the existence of low density marginal phases of the basic intrusions. These marginal phases must be very large and interpretation of the gravity data in this way would require the total width of the intrusion to be 100-150 km in the Pletipi Lake area and about 250 km in the Magpie Lake area.

The frequency of these intrusions, their enormous areal extent and their thickness raise problems with respect to the behaviour of the crust to such loads and the space problem attendant with their intrusion. It would seem reasonable to expect the crust to deform under such loads. However, these intrusions are spaced sufficiently closely that the broad regional anomalies produced by crustal warping or collapse may interfere with and mask each other.

At a density contast of 0.3 g/cm^3 the maximum thickness of the intrusions varies from about 7 to 15 km, but for all but the Red Wine intrusion a density contrast as low as 0.2 g/cm^3 could be used for the interpretation. At a density contrast of 0.2 g/cm^3 the basic intrusive rock must extend nearly to the base of the crust in some areas and the shape of the intrusions differs slightly from that for a density contrast of 0.3 g/cm^3. At the lower density contrast the intrusions have a long central pipe surrounded by a veneer of basic rock extending tens of kilometres into the areas adjacent to the pipe.

The ratio of the width of the structures to their thickness, which is as large as 15:1, indicates that these intrusions are broadly sheet-like. However, in detail there appears no doubt that the contacts dip inwards.

The anomalous mass has not been calculated from each of the anomalies because the complex regional field makes it difficult to isolate the local anomaly. However, the anomalous mass per unit length of anomaly can be estimated from the gravity profile using the formula

$$2\pi GM = \int_{-\infty}^{\infty} \Delta g(x)\, dx \ ,$$

where M is the anomalous mass per unit length, $\Delta g(x)$ the anomaly at a point x and G the gravitational constant. This formula is derived from Gauss's theorem. The two dimensional anomalous mass for each of the anomalies is, according to the above formula, of the order of 10^{12} grams per unit of length.

It has been noted previously that the local positive anomalies do not occur west of about 73°W. Anorthosites do occur to the west of this longitude, but the anomalies over them are negative if any anomaly occurs. Two of these, the Morin intrusion north of Montreal and the Adirondack massif in the northern part of the State of New York, have been studied by Thompson and Garland (1957) and Simmons (1964) respectively. The major problem with both interpretations has been the definition of the density contrast because measurements in both areas indicated little density difference between the anorthosites and the country rock. It is emphasized that there can be no doubt of the source of the negative anomalies because the correlation between the distribution of the gravity anomalies and the anorthosites leaves no question with regard to the source of the anomaly. Simmons assumed a density contrast of $-0.1\ g/cm^3$ and computed the thickness of the anorthosite to be about 4 km. Garland and Thompson assumed a much lower density contrast and obtained a maximum thickness of about 12 km.

The vast amount of intrusive rock exposed within the Grenville province indicates that widespread partial fusion in the upper mantle probably took place between 1000 and 1400 my ago. It is interesting to compare this to the present day situation in the Canadian Arctic and the Cordilleran region of North America where recent geophysical results (Niblett, Whitham and Caner, 1969) have suggested the presence of a zone of unusually high temperature at a depth roughly equivalent to the base of the crust. The crustal seismic results indicate that although this is an area of high topography, the crust is only about 30 km thick in the Cordillera in the United States. If this area is in isostatic equilibrium then the material compensating for the topography is likely the hot material in the upper mantle and perhaps the lower crust. If this hot material represents a partially fused upper mantle then widespread intrusion of fused material into the crust could take place under the right conditions. The end result might not be too different from what is seen in the Grenville today, although the intrusions might be of a different kind. This brings up the fascinating possibility that geophysicists a billion years from now may have one or two more Grenville-like problems on their hands.

CHAPTER 7

CONCLUSIONS

Comparison of the regional Bouguer and free anomaly maps with the topography suggests that the regional topography of northern Quebec is largely compensated. Comparison of the free air and isostatic anomalies along the 70th meridian indicates that the free air map provides a good approximation to an isostatic anomaly map. Analysis of the free air anomaly map shows that the gravity field is regionally depressed around Hudson Bay. It is concluded that the interpretation of Innes and Argun Weston (1966), that the regionally depressed field is due to incomplete isostatic recovery upon deglaciation, best explains this regional trend.

The interpretation of the gravity anomalies over the three structural boundaries of the Canadian Shield in northern Quebec has shown that the observed changes of Bouguer anomaly can be explained by an edge effect over different crustal blocks. This interpretation requires a thicker crust in areas where the gravity anomalies are high. This hypothesis is consistent with seismic results obtained in several areas of North America. The interpretation ignores the effect of processes influencing the development of crustal structure on the upper mantle. This assumption conflicts with the results of some seismic experiments in Canada, but it is believed that the hypothesis of compensated crustal structures can be extended to include variations of density in the upper mantle.

Within the Superior province, particularly in the Ungava Peninsula, there is a persistent correlation between high gravity anomalies and occurrences of granulites. In this province there is little evidence that occurrences of granitic rocks cause low gravity anomalies as is often found in other areas.

These relationships might be expected in areas where regional metamorphism has caused widespread formation of granulites at depth which have subsequently been exposed by a long period of erosion.

Interpretations of local anomalies have been confined to six anomalies over anorthositic intrusions in the Grenville province. This study has indicated that these basic intrusions have inward dipping contacts and a minimum density contrast of about 0.2 g/cm^3. On the assumption that the density contrast is 0.3 g/cm^3 these intrusions extend to depths of about 10 km or more. The computer programs based on the matrix method described in Chapter 3 have proved extremely useful in arriving at these conclusions.

The interpretation has been hampered by lack of data in nearly all the areas. A major conclusion must be the need for more work in gravity and other disciplines. Much more geological work is needed in the area to the east of the Labrador Trough and in the vicinity of the large anorthositic intrusions in the Grenville province. This work should be coupled with a program to provide a comprehensive and well catalogued set of density measurements. Low level aeromagnetic anomaly maps will undoubtedly prove valuable in defining the contacts of the large intrusions in the Grenville province.

Seismic work is essential in several parts of northern Quebec. In the vicinity of the structural boundaries, seismic work provides the best means of testing the hypothesis used to interpret the gravity anomalies and should provide important information regarding the contribution of lateral density variations in the upper mantle to the observed changes of gravity anomaly. However, it would seem desirable that a long north-south seismic profile in the Superior province is also carried out. Geochemical studies suggest that the upper crustal rocks become progressively more basic northward within the Superior province. It is important to know whether the crust also thickens gradually northward and whether the development of the granulites in the Ungava Peninsula has affected the upper mantle. The gravity data cannot provide a direct answer to this problem partly because of complications due to the presence of a regionally depressed field around Hudson Bay. However, a knowledge of the gravity field will undoubtedly prove useful in the interpretation of any seismic results obtained in the central and northern parts of the Superior province in northern Quebec.

APPENDIX 1

SPECIFICATIONS FOR THE SEDIMENTARY BASINS AND THE GRANITE BODIES PROGRAMS

PROGRAMMING LANGUAGE: PL/1

PURPOSE: These programs will automatically produce a model, either in the form of sedimentary basin (Fig. 1-1b) or a granite body (Fig. 1-1d), that can give rise to a specified observed anomaly.

METHOD: The observed anomaly is assumed to lie on a horizontal plane surface from which m observations are taken along a profile normal to the strike of the anomaly. The unknown structure is subdivided in $n (n \leq m)$ rectangular blocks and the following specified:

1. the margins of the blocks, and
2. the strike length, if finite, in either direction normal to the plane of the profile.

The depth to the upper surface of the structure must be equal to, or greater than, that of the horizontal plane of the observed anomaly. In the granite bodies program the upper surface is given for the block, the k th *, underlying the extreme value of the anomaly. Finally, the density contrast, assumed uniform throughout the anomalous mass, is specified.

* In the program the integer block = k

APPENDIX

SPECIFICATIONS FOR THE SEDIMENTARY BASINS AND THE GRANITE BODIES PROGRAMS

PROGRAMMING LANGUAGE: PL/1

PURPOSE: These programs will automatically produce a model, either in the form of sedimentary basin (Fig. 1-1c) or a granite body (Fig. 1-1d), that can give rise to a specified observed anomaly.

METHOD: The observed anomaly is assumed to lie on a horizontal plane surface from which m observations are taken along a profile normal to the strike of the anomaly. The unknown structure is subdivided in n(n ≤ m) rectangular blocks and the following specified:

1. the margins of the blocks, and
2. the strike length, if finite, in either direction normal to the plane of the profile.

The depth to the upper surface of the structure must be equal to, or greater than, that of the horizontal plane of the observed anomaly. In the granite bodies program the upper surface is given for the block, the k th,*, underlying the extreme value of the anomaly. Finally, the density contrast, assumed uniform throughout the anomalous mass, is specified.

The formulae used to calculate the gravity effect apply to two dimensional blocks. Three dimensional structures are approximated by end corrections (Nettleton, 1940). The gravity effect of a two-dimensional rectangular block is calculated using Heiland's (1946) formula. An approximation to this formula obtained by assuming the mass to be concentrated along a horizontal plane through the centre of the block is used when the depth to the centre of the block is equal to, or greater than, twice the thickness.

In the first step of the production of the model the blocks are assumed to form a thin sheet along the upper surface of the structure. The set of linear equations

$$\Delta g_i = K_{ij} \cdot \rho_j, \quad (j = 1\text{---}n, \; i = 1\text{---}m, \; n \leq m) \qquad (1)$$

where K_{ij} is the kernel function giving the gravity effect per unity of density contrast of the j th rectangular block at the i th field point, are solved for density contrast (ρ_j) of each block - directly if $m = n$ and by least squares if $m > n$. These blocks of non-uniform density contrast are transformed to give blocks of uniform density contrast on the basis that the mass of each block is constant. The latter are arranged to approximate the outline of either a sedimentary basin or a granite body (Fig. 1-1b, d) and then the gravity effect of this first model is calculated. The calculated and observed anomalies are compared to determine the residual anomaly at each field point.

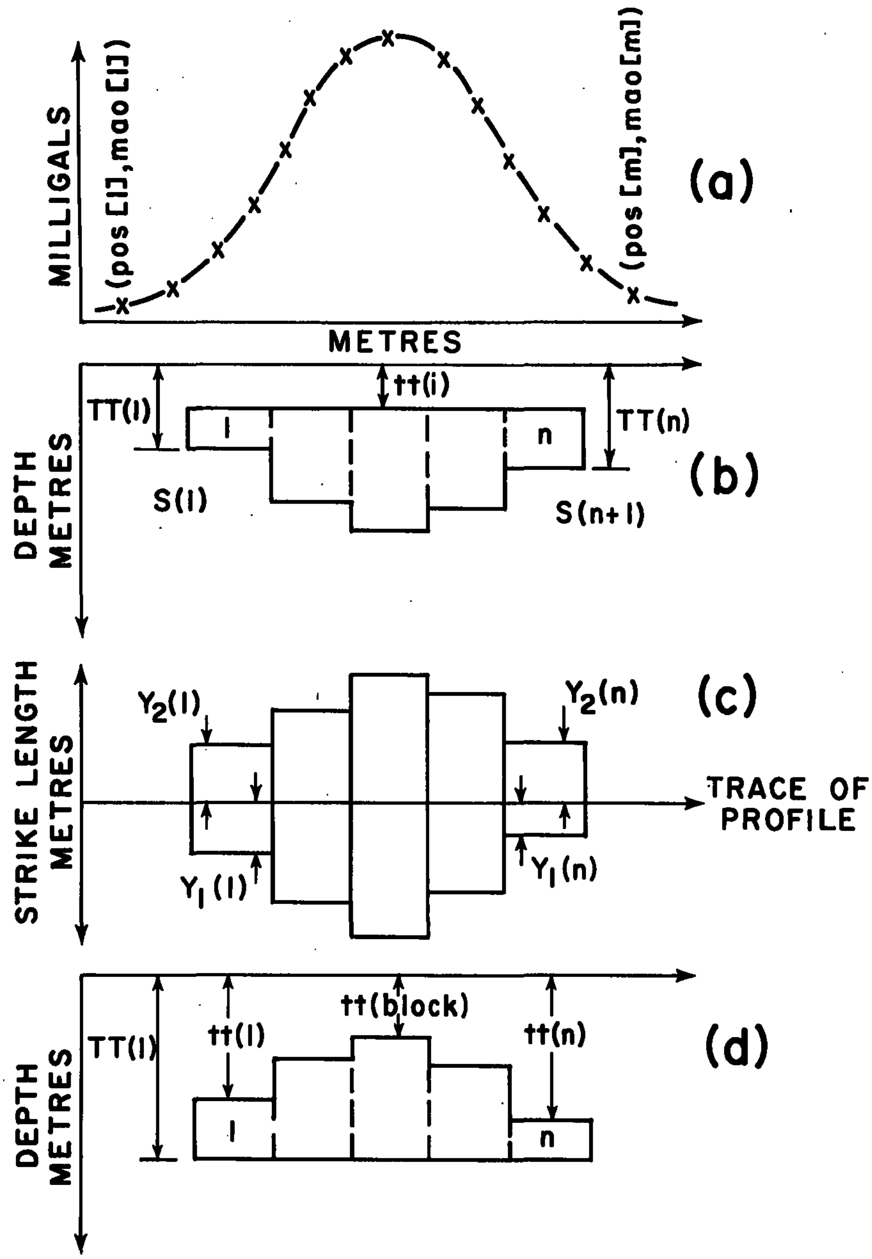


Fig. A-1-1
Explanation of symbols used in Sedimentary Basins and Granite Bodies programs; (a) observed anomaly; (b) sedimentary basin model; (c) plan view of models; (d) granite bodies model.

The next step in the method is the adjustment of the model. This is accomplished by adding thin blocks to the unknown surfaces of the model. These are:

(a) all lower surfaces of the sedimentary basin model, and

(b) all upper surfaces, the k th excluded, and the flat lower surface of the granite body model.

The linear equations (1) are again set up and solved for ρ_j on the basis of residual anomalies and the transformation repeated to give the adjustment in terms of blocks of uniform density contrast. The gravity effect of the adjustment is calculated and the residuals are corrected.

The adjustment of the model will continue until either the residuals are all less than a specified limit or the number of adjustments requested by the interpreter has been made. Instability can usually be avoided by choosing block widths which are greater than the depth to the upper surface. In the sedimentary basin program instability can sometimes only be avoided at the expense of great loss of detail regarding the shape of the structure. Consequently a method 2, which uses the existing blocks and the total anomaly to estimate the adjustment to each block has been introduced. Method 2 is not available with the granite bodies program.

Both programs contain a facility for re-starting. The depths to the unknown surface must be provided. In this case the programs carry out the adjustment only.

DATA FORMAT

(a) Sedimentary Basins

```
cycle;

modelname
iteration; limit; noest; n; m; p3; pp;
ro(1);----ro(p3)

us(1);----us(pp)

pos  (1)   ;          mao  (1)  ;
....       ;          ....      ;

....       ;          ....      ;

pos  (m)   ;          mao  (m)  ;

S  (1)     ;          y1   (1)  ;     y2  (1) ;  (TT  (1) )  ;

....       ;          ....      ;     ....    ;  ....         ;

....       ;          ....      ;     ....    ;  ....         ;

S  (n)     ;          y1   (n)  ;     y2  (n) ;  (TT  (n) )  ;

S (n+1)    ;

flow; lines;
```

(b) Granite Bodies

```
cycle;
modelname
iteration; limit; noest; n; m; p3; pp; block;
ro(1) ;   ro(p3)
us(1) ;   us(pp) ;

( TT(block ) );

pos  (1) ;          mao (1)   ;

....     ;          ....      ;

....     ;          ....      ;

pos  (m );          mao ( m)  ;

S    (1) ;          y1  ( 1 ) ;   y2 (1) ;  (tt (1) )  ;

....     ;          ....      ;   ....   ;  ....       ;

....     ;          ....      ;   ....   ;  ....       ;

S (n)    ;          y1  ( n)  ;   y2 ( n) ; (tt (n) )  ;

S(n+1)   ;
```

NOTES ON DATA FORMAT

(a) Cycle specifies the number of different models to be processed during any given operation on the computer. This is the only entry which is not repeated for different models.

(b) Modelname is a 60 character or less name - any valid character may be included and multiple 5/8 punches must precede and follow the name.

(c) Iteration specifies the number of adjustments to any model:-

-try 2 for method 1

-4 or 5 for method 2 (sedimentary basins only)

(d) Limit defines the goodness of fit to the observed anomaly:-

-try 0.5 to 1 mgal.

(e) Noest provides for re-starting:

-0 if no estimate provided

-1 if an estimate provided

Note that the bracketed quantities are included only if noest equals one

(f) n is the number of blocks

(g) m is the number of observations (m≫n)

(h) p3 is the number of different density contrasts

(i) pp is the number of different depths to the upper surface

(j) ro is an array containing the assumed density contrasts

(k) us is an array containing the assumed depths to the upper surface

(l) Block is used in granite bodies only and specifies the number of the block, counted from the left, whose upper surface is fixed.

(m) TT block is used in the granite bodies program. It is the depth to the base of the structure and is used when re-starting.

(n) Pos and Mao are arrays giving the position and value of the anomalies respectively.

(o) S, y1, y2 are arrays defining the margins of the blocks and the strike length of the blocks in either direction normal to the plane of the profile. For two-dimensional structures y1 (i) = y2 (i) = 0.

(p) The TT array is used when re-starting the sedimentary basin program. It defines the depths to the lower surfaces of the blocks.

(q) The tt array is used when re-starting the granite bodies program. It specifies the depths to the upper surfaces of the blocks.

(r) Flow and Lines are used in the sedimentary basin program to define the type of adjustment:-

0	0	- method 1,
100	0	- method 2,
100	100	- method 2 for three adjustments and the remainder by method 1.

OUTPUT

The results of each adjustment are printed complete with explanatory headings. In the granite bodies program the margins of the k th block are those of the left and right borders of the structure.

GENERAL NOTES

(a) Lengths are in metres, anomalies in milligals and densities in grams per cubic centimetre.

(b) the gravity anomalies and density contrasts are treated as positive quantities.

(c) The block widths should be greater than the depth to the upper surface.

(d) Large variations of the block width are not recommended.

THE PROGRAMS

This section is not necessary to the operation of the programs. It is intended to provide additional information to those who may wish to modify them.

The programs are a series of procedures under the control of a short main program. The main program reads the data and controls the arguments used in the procedures. The procedures and their purpose are as follows:

(a) SYMDET, SYMSET which carry out the necessary matrix operations are PL/1 translations of Algol programs (Martin, Peters and Wilkinson, 1965).

(b) ENDCOR computes the end corrections using Nettleton's (1940) method

(c) INVTAN computes the inverse tangents needed in the formulae used to give the exact and approximate gravity effect of two-dimensional rectangular blocks,

(d) CALCBLOCK calculates the exact or the approximate gravity effect of the blocks,

(e) SORTOUT is a housekeeping procedure which overseas the arguments used in the procedures ENDCOR, INVTAN, and CALCBLOCK,

(f) DECIDE examines the distribution of blocks and sets up two arrays:- one to indicate whether the exact or the approximate equation is to be used and the other to give the sign of the calculation - there being one entry in each array for each block,

(g) CALCUL is used to control the computation of the gravity effect at each field point,

(h) FORM is basically another overseeing procedure which

(i) controls the computation of the kernel array,

(ii) if a least squares solution is needed, it sets up

(iii) calls upon the matrix procedures to solve the system of linear equations for ρ_j,

(i) OUT provides for output,

(j) RESIDUAL calculates the residual anomalies at each field point.

APPENDIX 2

SPECIFICATIONS FOR THE (SINX)/X PROGRAM

PROGRAMMING LANGUAGE: FORTRAN IV

PURPOSE: To carry out a two dimensional isostatic study and a two dimensional Bouguer interpretation.

METHOD: It is assumed that the compensating mass is concentrated along a plane surface at a specified depth and that there is a jump in density across this surface. The Bouguer interpretation is carried out on the assumption that the mass giving rise to the observed anomaly is also concentrated along the same plane surface.

The computations are based on formulae derived by Tomoda and Aki (1955) and Shimazu (1962). The quantities calculated are as follows:

(a) Isostatic

(i) Anomaly

$$\Delta g_n^1 = \Delta g_n + 2\pi G\rho \sum_s H_s \Phi^1_{n-s} \quad ,$$

(ii) Mass

$$\Delta M_n^1 = \frac{1}{2\pi G} \sum_s \Delta g_s \Phi^1_{n-s} + \rho H_n \quad ,$$

(iii) Relief

$$\Delta h_n^1 = \Delta M_n^1 / \; (\rho^1 - \rho) \quad ,$$

(b) Bouguer

(i) Downward continued anomaly

$$\Delta g_n^0 = \sum_s \Delta g_s \Phi_{n-s}^0 ,$$

(ii) Subterannean surface mass

$$\Delta M_n^0 = \frac{1}{2\pi G} \sum_s \Delta g_s \Phi_{n-s}^0 ,$$

(iii) Crustal relief

$$\Delta h_n^0 = \Delta M_n^0 / (\rho^1 - \rho) ,$$

where Δg_n = observed Bouguer anomaly,

H_n = elevation,

ρ^1 = assumed density of the material beneath the level of compensation,

ρ = assumed density of the material above the level of compensation,

G = constant of gravitation

$$\Phi_{n-s}^0 = \frac{d'}{\pi(d'^2+(n-s)^2)} (\pm e^{d'\pi}-1),\ (n-s)\ \begin{matrix}\text{even}\\ \text{odd}\end{matrix}$$

$$\Phi_{n-s}^1 = -\frac{d'}{\pi(d'^2+(n-s)^2)} (\pm e^{-d'\pi}-1),\ (n-s)\ \begin{matrix}\text{even}\\ \text{odd}\end{matrix}$$

d' = ratio of depth to plane surface and grid interval.

The following are important to the application of the (sin x)/x method:

(a) the calculations at the end points of the profile are inaccurate because the anomaly is assumed zero beyond the ends of the profile,

(b) $\sum_{-n}^{n} \phi_n^o \approx \sum_{-n}^{-n} \phi_n^1 \approx 1$

which usually requires that the spacing between grid points be greater than the linear depth to the specified surface.

(c) for isostatic studies the measurements should be smoothed by averaging or some other process.

(d) the units are:

gravity anomalies - milligals

densities - grams per cubic centimetre

elevations - metres

all other distances - kilometres

INPUT

```
a ;     g;    k;     m
rhoman;
DLA(1) ;     DLO(1) ;     B(1)  ;     H(1) ;
---    ;     ---    ;     ---   ;     --- ;
---    ;     ---    ;     ---   ;     --- ;
DLA(g) ;     DLO(g) ;     B(g)  ;     H(g) ;
                          CD(1) ;-----CD(k) ;
                           R(1) ;----- R(k)  ;
```

(a) <u>a</u> is the grid spacing

(b) <u>g</u> is the number of grid points - <u>this must be odd</u>

(c) <u>k</u> is the number of different levels of compensation assumed

(d) <u>m</u> is the number of different mean densities assumed for the material above the particular plane of compensation

(e) <u>rhoman</u> is the assumed density of the material beneath the plane of compensation

(f) DLA and DLO are arrays which specify the locations of the observations.

(g) B is the array of observations.

(h) H is the array of elevations

(i) D contains the different depths at which compensation is assumed to take place.

(j) R contains the different densities assumed for the material above the plane of compensation

OUTPUT

The output is complete with self explanatory headings. The sum of the weighting coefficients is printed once for each different level of compensation.

APPENDIX 3

SPECIFICATIONS FOR PROGRAMS TO ADJUST GRAVIMETER AND PENDULUM NETWORKS

PROGRAMMING LANGUAGE: FORTRAN IV

PURPOSE: To compute the most likely values of gravity of the control stations and the scale constants of the gravimeters from a network of pendulum and gravimeter observations by the method of least squares.

METHOD: The basic theory is given by Cook (1954) and reference should be made to this paper prior to utilizing the program. Basically there should be a network of gravity stations connected to one or more other gravity stations by one or more gravimeter or pendulum observations. From this network one station must be selected as the "base" (g_0). This station will not appear in the solution but all connections between it and any other control station will be included in the adjustment.

Consider a network of n+1 control stations connected by a total of m pendulum and gravimeter observations; the gravimeter connections being made by q different gravimeters. The observation equations ($m \geqslant n + q$) for this network are:

(i) pendulum connections

$$(g_i + \Delta g_i) - (g_j + \Delta g_j) = \Delta g_{ij}, \quad \begin{matrix}(i = 0,1---n) \\ (j = 0,1---n)\end{matrix},$$

(ii) gravimeter connections

$$(g_i + \Delta g_i) - (g_j + \Delta g_j) = \Delta g_{ij} (1 + \Delta K_p),$$

$$(p = 1,2,---q),$$

where g_i and g_j are trial gravity values for the ith and jth stations

K_p is the trial scale constant for the pth instrument.

Δg_{ij} is the observed gravity differences for the interval i-j

ΔR_{ij} is the observed gravimeter difference in instrument divisions for the interval i-j

Δg_i and Δg_j are the unknown corrections to the ith and jth trial gravity values, and

ΔK_p is the unknown correction to the pth trial scale constant.

The pendulum and gravimeter observation equations can now be combined to give the matrix equation

$$\begin{bmatrix} \underline{P} & \underline{O} \\ \underline{G} & -\underline{R} \end{bmatrix} \cdot \begin{bmatrix} \underline{D} \\ \underline{K} \end{bmatrix} = \begin{bmatrix} \underline{g}_p \\ \underline{g} \end{bmatrix}$$

where $\underline{O}$ is a null matrix. If the observations are weighted then the elements of $\underline{P}$ and $\underline{G}$ are $\pm\sqrt{W_{ij}}$ or O and the elements of $\underline{g}_p$ and $\underline{g}$ are multiplied by $\sqrt{W_{ij}}$. The above matrix equation can be written as $\underline{T}\ \underline{x} = \underline{g}$,

where $\underline{T}$ is an array of dimension (mx(n+q)), $\underline{x}$ is a vector of dimension (n+q) and $\underline{g}$ is a vector of dimension m. If $\underline{T}^T$ is the transpose of $\underline{T}$ then the solution $\underline{x}$ can be obtained by multiplying both sides of the matrix equation by $\underline{T}^T$ and then inverting the system to give

$$\underline{x} = \left[\underline{T}^T\underline{T}\right]^{-1} \underline{T}^T\underline{g}$$

If Δg_o be the observed gravity difference and Δg_c be the adjusted value, the standard deviation of an observation of unit weight is

$$\sigma_s = \sqrt{\frac{\sum_i w_i(\Delta g_o - \Delta g_c)_i^2}{m-n-q}}$$

The standard deviations of the unknowns can now be calculated using the relation $\sigma_i = \sigma_s \sqrt{N_{ii}}$ where N_{ii} is the appropriate diagonal term of the inverse matrix $\left[\underline{T}^T\underline{T}\right]^{-1}$.

The distribution of the residuals is given in a histogram and the normal distribution with the same standard deviation (σ_s) calculated for the same intervals.

The adjustment is carried out in two separate programs. The first of these assigns sequence numbers to the unknowns and then punches out the observation equations to be used in the second program which carries out the adjustment.

INPUT - OUTPUT (NET EDIT)

1. Edit Card

   - for no card output IEDIT = 0

2. Control Station cards

   - one for each station giving number and trial gravity value.

   - last card must contain 999999 in cols. 4-9

3. Instrument cards

   - one for each instrument, instrument year, or instrument-trip giving instrument number and trial scale constant.
   - last card must contain 999999 in cols. 1-6

4. Instrument Equivalence Cards

   (a) flow card

      - equals 0 if no instrument equivalenced

   (b) equivalence cards

      - gives instrument and scale constant respectively of instrument involved in the order "from-to".
      - last card must contain 999999 in cols. 5-10.

5. Observation Cards

   - one for each observation giving the weight of observation, the interval measured, the instrument used (0 if pendulum), and the corrected difference of reading (gravity difference if pendulum).
   - last card must contain 99999 in cols. 1-5.

The output from this program is a listing of all data, properly sequenced, pertinent to the adjustment and, if not solely an editing run, the corresponding card output.

INPUT - OUTPUT (NET ADJUST)

This could be prepared manually for small networks, but it is recommended that "Net Edit" be used as the preliminary step. The output from Net Edit appears in the order:

1. sequenced observation cards
2. control stations cards
3. instrument cards
4. summary card

This deck must be rearranged manually to conform to the order specified below.

1. Flow card
   - to print normals INO = 1, otherwise INO = 0
   - to print inverse IIO = 1, otherwise IIO = 0
   - to adjust scale constants IFL = 1, otherwise IFL = 0
   - to provide statistics of each gravimeter IFI = 1, otherwise IFI = 0
2. Summary card
   - total number of unknowns (NN)
   - number of unknown control stations (IB)
   - number of unknown scale constants (IG)
3. Control Station cards
   - one for each unknown

4. Instrument cards

   - one for each unknown

5. Observation cards

   - one for each observation

   - last card must contain 99999 in cols. 2-6 or 999.99 in cols. 1-6.

The output from Net Adjust is a self-explanatory listing giving

1. the normal matrix (if requested)
2. the value of the determinant
3. the inverse matrix (if requested)
4. the solution
5. the residuals ($g-\underline{Tx}$)
6. the observations with residuals
7. the statistics
8. the histogram of residuals and the corresponding normal distribution

General Notes

1. The units are instrument divisions, gravity differences in milligals, gravity values in gals and scale constants in milligals per division.
2. The details of the card formats can be obtained from the Fortran listing.

3. With the exception of the formation of the normals all computations are carried out in double precision and rounded to single precision at their completion.

4. The matrix operations are carried out using a package originally written for the IBM 7094, University of Toronto. Modifications and additions have been made by Dr. D. Nagy of the Observatory.

5. Although the programs were written primarily to adjust "gravity" networks containing indirect measurements by gravimeter, the specification IFL = 0 permits the adjustment of networks of direct measurements (e.g. levelling networks).

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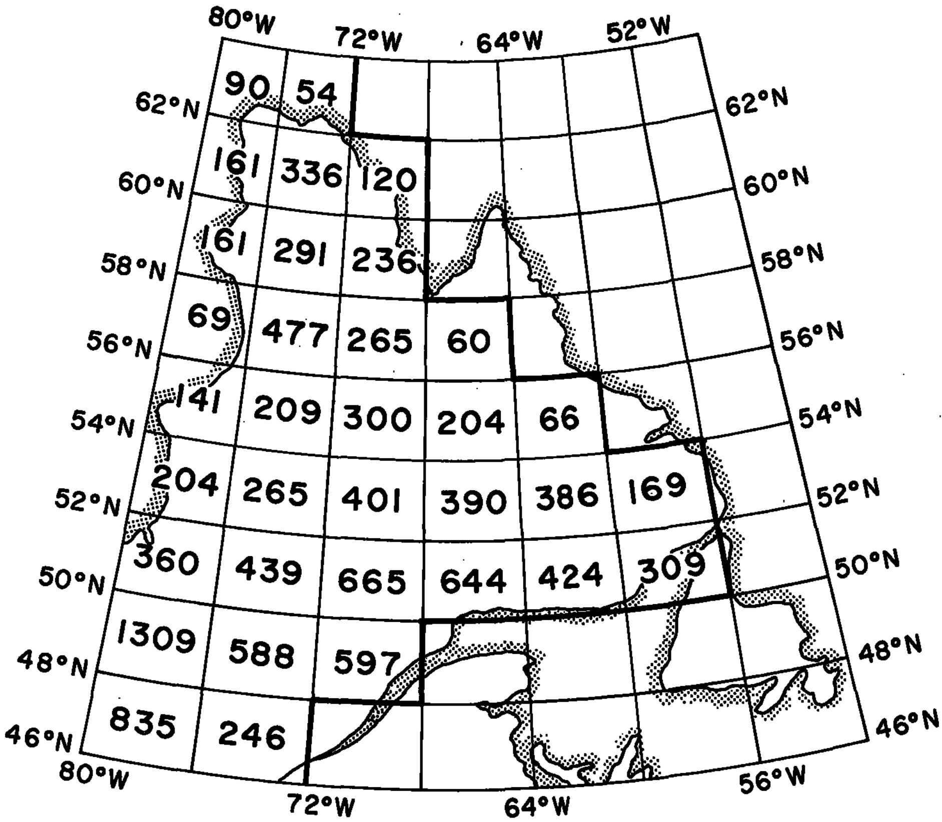


Fig. 4-4

Distribution of gravity stations by areas of $2^{\circ} \times 4^{\circ}$ in northern Quebec.

of an "intermediate or basaltic" layer in the crust. The only published reference to such a layer within the Canadian shield is that of Hall and Brisbin (1965) who studied the crustal structure in northern Manitoba using second as well as first arrivals. Thus far, Hall and Brisbin are the only Canadian seismologists who have relied extensively on second arrivals for an analysis of crustal structure.

The remaining seismic results that require mention are those of Barr (1967) and Brune and Dorman (1963). Barr analysed the first arrivals at seismic observatories in eastern Canada from the largest chemical explosions used in the Hudson Bay and Lake Superior experiments. He concluded that the model of the earth's upper mantle and crust which gave the best fit to the data was a four-layered model for which the P-wave velocity increased with each successive layer. He also noted that a P-wave low velocity layer is not required to explain the data and suggested that this might be connected with low heat flow values reported in the shield. This result can be contrasted with that of Brune and Dorman who, from a study of Rayleigh waves which traversed the eastern Canadian Shield, suggested that there is a low velocity S-wave channel. Their results indicate a low velocity channel some 200 km thick at a depth of 100 km.

4-6. Correlation of Gravity and Geology

The Bouguer anomaly map in the pocket (see also Figs. 5-3, 5-7, 5-9) has been compiled from maps at a scale of 1:500,000 based on the distribution of stations shown in Fig. 4-4. The anomalies, which cover a range of about 160 mgal but are predominantly negative, range from a minimum of -130 mgal along the Grenville Front to a maximum of +30 mgal over a basic intrusion near Sept Iles on the northern shore of the St. Lawrence River.

Within the Superior province of northern Quebec the gravitational field is generally flat and devoid of local anomalies with the main exception of those over the region of granulites located in the northern part of the Superior province immediately to the south of the Cape Smith Belt. The principal reason for the lack of local anomalies within the Superior province of Quebec appears to be the absence of infolded Keewatin basic and sedimentary rocks (Innes, 1960) which produce local positive anomalies of the order of tens of milligals in the Superior province of Ontario.

In contrast to the Superior province the gravitational field over the Grenville province is quite variable, particularly in the northeast where, large, in both area and amplitude, local anomalies are observed over anorthositic intrusions. In addition, there are several, though less prominent, local negative anomalies over low-density, acidic intrusions. Some of these local negative anomalies are associated with pure anorthosite, and the results of geophysical investigations of these masses have been published (Thompson and Garland, 1963; Simmons, 1962) or are in progress. The primary interest in this work lies in the positive anomalies associated with the basic intrusions, but reference will be made again to these completed investigations.

The portions of the Churchill province covered by gravity observations are the northern tip of the Ungava Peninsula from the Cape Smith Belt northward to Hudson Strait and the Labrador Trough. Aside from the linear anomalies over the structures marking the boundaries, the main characteristic is the generally higher level of the anomalous field north of the Cape Smith Belt than observed in the Superior province to the south. Recent measurements in Hudson Bay and Hudson Strait (Innes, Goodacre, Weber, McConnell, 1967) show that this small area of positive anomalies is part of a much larger zone of relatively positive anomaly which extends hundreds of miles to the north, east and west of the northern tip of the Ungava Peninsula. Innes et al (1967) suggest that the source of this anomaly may be relatively high grade metamorphic rocks produced by the Hudsonian orogeny.

The major anomalies on the map are those in the area of the structural boundaries and those over the anorthositic intrusions within the Grenville province. Of the anomalies over these boundaries only one, the Cape Smith Belt, is completely mapped. The gravity data are incomplete over the eastern end and the northern flank of the eastern extension of the Grenville anomaly and a similar situation exists along the eastern margin of the anomaly over the Labrador Trough. These three major anomalies differ from each other in some respects, but all have in common the presence of linear, negative anomalies with widths of the order of hundreds of kilometres and relatively gentle horizontal gravity gradients.

In the Cape Smith region there is a central positive anomaly flanked by negative anomalies. The positive anomaly occurs over the basic volcanic and intrusive rocks of the Cape Smith Belt. In fact, the anomaly follows the boundaries of the Cape Smith Belt sufficiently closely to leave no doubt that the basic rocks are the cause of the anomaly. The source of the flanking negative anomalies is not so obvious. Granitic rocks do outcrop in the area of the southern negative anomaly, but there is no evidence from the geological maps to indicate that these granites are confined mainly to a linear zone underlying the negative anomaly. Tanner and McConnell (1964) suggested that the flanking negative anomalies are caused by structure at the base of the crust. The evidence for their interpretation will be reviewed in the light of additional gravity data and the seismic results in Hudson Bay.

The gravity field over the Grenville Front has been interpreted by Innes (1957) and Grant (1968). Innes suggested that the granites caused the anomaly and Grant postulated a very thick accumulation of low density sediments as the source. There is no clear evidence from the known surface geology for either interpretation, which might be suggested from the fact thattwo different interpretations of the anomaly have been given. Sediments and granites are present in places along the Grenville Front, but neither occur continuously along the length of the structure. The interpretation of this anomaly is complicated by the presence of several of the enormous anorthositic intrusions within the Grenville province.

The negative gravity anomaly over the Labrador Trough would at first glance seem to relate to the sediments of the Labrador Trough. However, the anomaly extends between limits given approximately by Fort Chimo to the north and Schefferville to the south; a distance that is only one-half to two-thirds of the length of the exposed Labrador Trough. Also, the eastern half of the Labrabor Trough is composed mainly of basic volcanic and intrusive rocks. It is therefore doubtful that these rocks are the source of the negative anomaly.

The other group of anomalies considered in this interpretation are those associated with enormous anorthositic intrusions in the Grenville. This study is confined to six of the major intrusions lying between the approximate longitude limits of 73°W and 60°W. All of the anomalies over these major intrusions are positive, display steep horizontal gradients and correlate with exposed rocks. It is interesting to note that, whereas the anomalies are positive in this region, negative anomalies are usually observed over anorthositic intrusions to the west of 73°W (Thompson and Garland, 1957 ; Simmons, 1960). However, there can be little doubt that the anomalies studied here are caused by the intrusions and that these intrusions are more basic than those to the west of 73°W.

4-7. Correlation of Topography and Gravity

It has been observed that the Canadian Shield is generally over-compensated isostatically (Innes, 1960; Shimazu, 1962). Although both Innes and Shimazu calculated isostatic anomalies - by different methods - in their studies, the same conclusion has been reached by comparing average values of Bouguer anomaly and elevation within the Shield. Many such comparisons show that the average Bouguer anomaly is more negative than expected on the assumption that the topography has the form of an infinite plane.

The existence of a depressed gravitational field indicates a mass deficiency in the region and raises a problem with respect to the ability of the earth's crust to support the corresponding load. Jeffreys (1962; see also Bott, 1965) has calculated that, for an earth consisting of an elastic crust overlying a mantle of negligible strength, structures 500 km or more wide reach isostatic equilibrium by elastic deformation. The major factor controlling the rate of adjustment is the rate of flow of the mantle which would appear to be of the order of a centimetre per year. It would therefore be expected that very wide structures would adjust isostatically at the approximate rate of one kilometer per ten thousand years.

Innes and Argun-Weston (1966) have analyzed the gravity data in the region surrounding Hudson Bay and find that the gravitational field becomes regionally more negative toward Hudson Bay. Since the Laurentide Ice Sheet covered most of the Canadian Shield, it is natural to suggest that the depressed gravity field is related to the recent ice age. Innes and Argun-Weston, who considered the gravity data in the context of data on raised beaches in the Hudson Bay area, concluded that this area was a centre of maximum loading during the ice age and that isostatic recovery subsequent to deglaciation is incomplete. They also estimated on the basis of raised beaches that recovery is taking place at a rate of about 1 cm/yr.

The interpretation of Innes and Argun-Weston is in good agreement with both theoretical considerations and results obtained in other areas such as Fennoscandia. The only uncertainty about the interpretation is the possibility that the Hudson Bay basin (including James Bay) has been a structural low since the early Palaeozoic. This basis for this remark is the presence of Ordovician and Silurian sediments to the west of James Bay, which were probably part of a

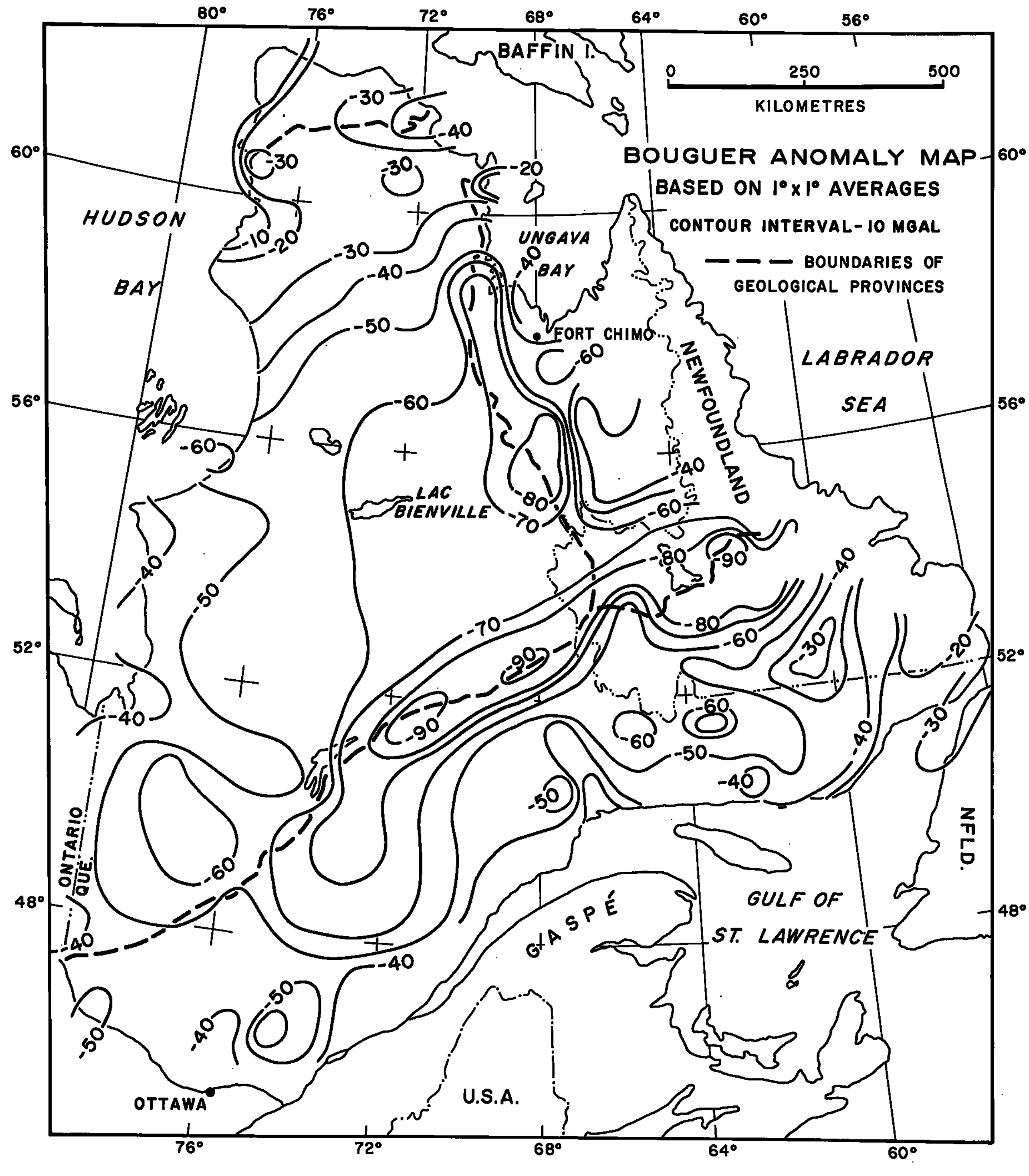

BOUGUER ANOMALY MAP
BASED ON 1°x1° AVERAGES
CONTOUR INTERVAL - 10 MGAL
BOUNDARIES OF GEOLOGICAL PROVINCES
0 250 500
KILOMETRES
BAFFIN I.
HUDSON BAY
UNGAVA BAY
FORT CHIMO
LABRADOR SEA
NEWFOUNDLAND
LAC BIENVILLE
NFLD.
GULF OF ST. LAWRENCE
GASPÉ
ONTARIO
QUE.
OTTAWA
U.S.A.
80° 76° 72° 68° 64° 60° 56°
60° 56° 52° 48°

Fig. 4-5

much more extensive sedimentary cover which has been eroded from all but the area of the Hudson Bay basin. The seismic results in Hudson Bay along the east-west profile between Churchill and Povungnituk show the Mohorovicic discontinuity to be roughly dome-shaped which is consistent with the concept that Hudson Bay is a basin. However, this model would not account for the depressed gravity field neither locally in the Hudson Bay area nor regionally throughout an area of the Shield that is thousands of kilometres by thousands of kilometres. Any alternative interpretation to that of Innes and Argun-Weston would involve density variations in the upper mantle for which there is at present no basis. Throughout the remainder of this study it will be assumed that the gravity field is regionally depressed throughout most of the Canadian Shield because of incomplete isostatic adjustment upon deglaciation.

The foregoing resumé provides the background necessary to focus attention on the situation in Quebec and the remainder of this section will be devoted to the mean Bouguer and free air anomaly maps of northern Quebec and to isostatic anomalies along a north-south profile at 70°W.

The regional Bouguer anomaly map (Fig. 4-5) shows the linear anomalies over the Grenville Front and the Labrador Trough clearly, but the east-west pattern of the Cape Smith region is not observed. Comparison of the regional Bouguer anomaly map and the regional topographic map of Fig. 4-3 indicates that there is an inverse correlation between Bouguer anomaly and topography. This is particularly evident in the central part of the region where the Bouguer anomaly field becomes progressively more negative toward

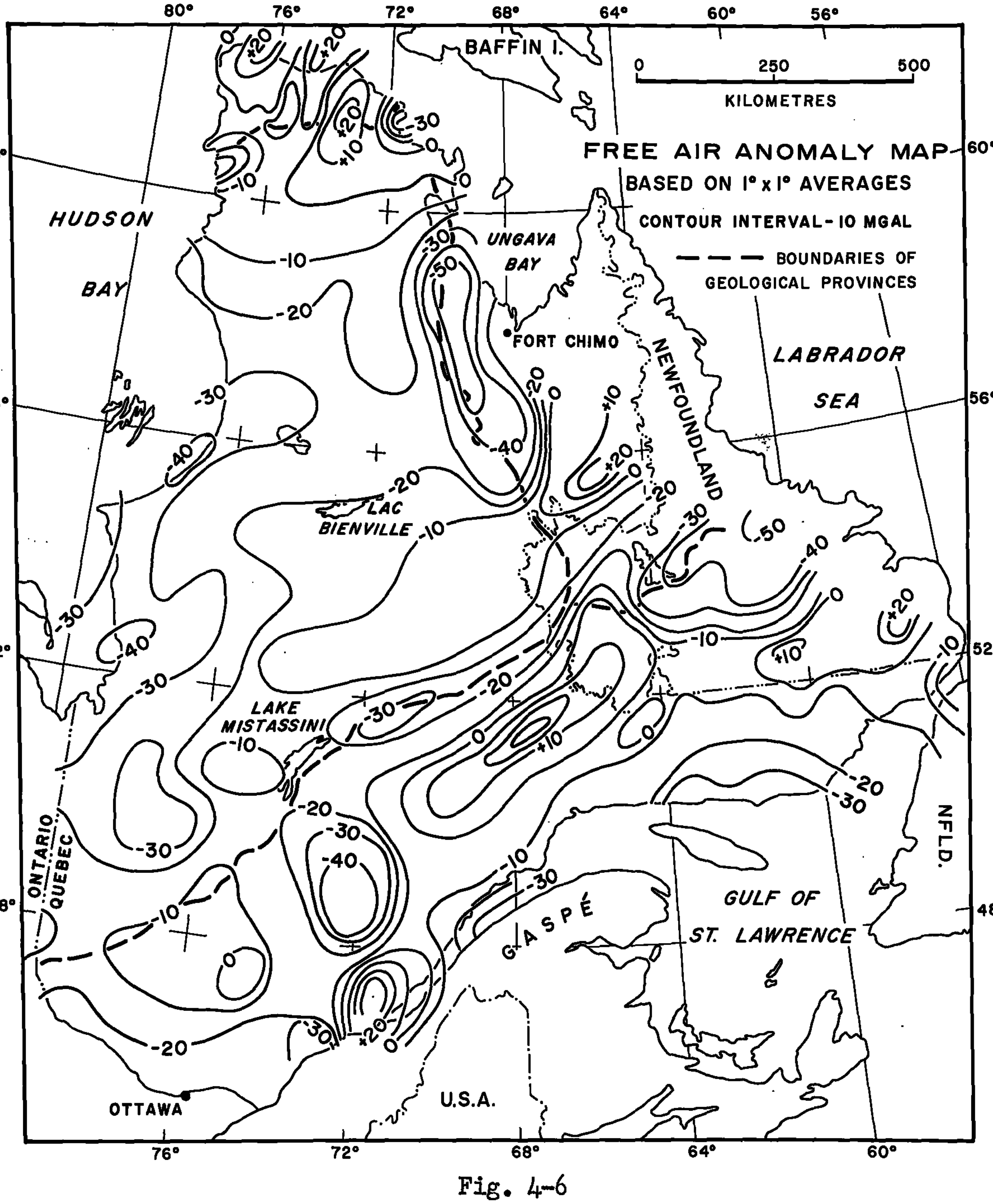

FREE AIR ANOMALY MAP
BASED ON 1° x 1° AVERAGES
CONTOUR INTERVAL - 10 MGAL
BOUNDARIES OF GEOLOGICAL PROVINCES
0 250 500
KILOMETRES
BAFFIN I.
HUDSON BAY
UNGAVA BAY
FORT CHIMO
NEWFOUNDLAND
LABRADOR SEA
LAC BIENVILLE
LAKE MISTASSINI
ONTARIO
QUEBEC
GASPÉ
GULF OF ST. LAWRENCE
NFLD.
U.S.A.
OTTAWA
80° 76° 72° 68° 64° 60° 56°
60° 56° 52° 48°

Fig. 4-6

the apex of the topographic dome. As an inverse correlation between Bouguer anomaly and elevation can be expected when topography is compensated at finite depth, it is concluded that the Bouguer hypothesis does not adequately account for the regional relationship of topography to compensation in northern Quebec. The presence of the topographic dome over the Grenville Front and the evidence from the regional Bouguer field for compensation of topography indicates that consideration of this effect will be necessary in the geological interpretation of the gravity data.

The regional free air anomaly map (Fig. 4-6) shows some significant differences from the regional Bouguer anomaly map. In the vicinity of the Grenville Front the gravity low is slightly more narrow on the free air anomaly map which is to be expected when dealing with a broad dome that is compensated at finite depth. In addition, the free air map shows a prominent gravity high to the south of the Grenville low. Although the average free air anomalies would not be uncorrelated with elevation for areas of 1° x 1°, comparison between the free air map and the topographic map of Fig. 4-3 indicates that the trends on the two maps south of the Grenville Front are not identical. This suggests that the positive free air anomaly south of the Grenville Front is at least partly real; that is, it is caused partly by lateral density variation within or beneath the Grenville province. This anomaly is not obvious on the Bouguer map probably because it is masked by the effect of compensation for topography.

Elsewhere on the free air anomaly map the progressive decrease of anomaly toward Hudson Bay is evident. It also appears that the negative anomaly

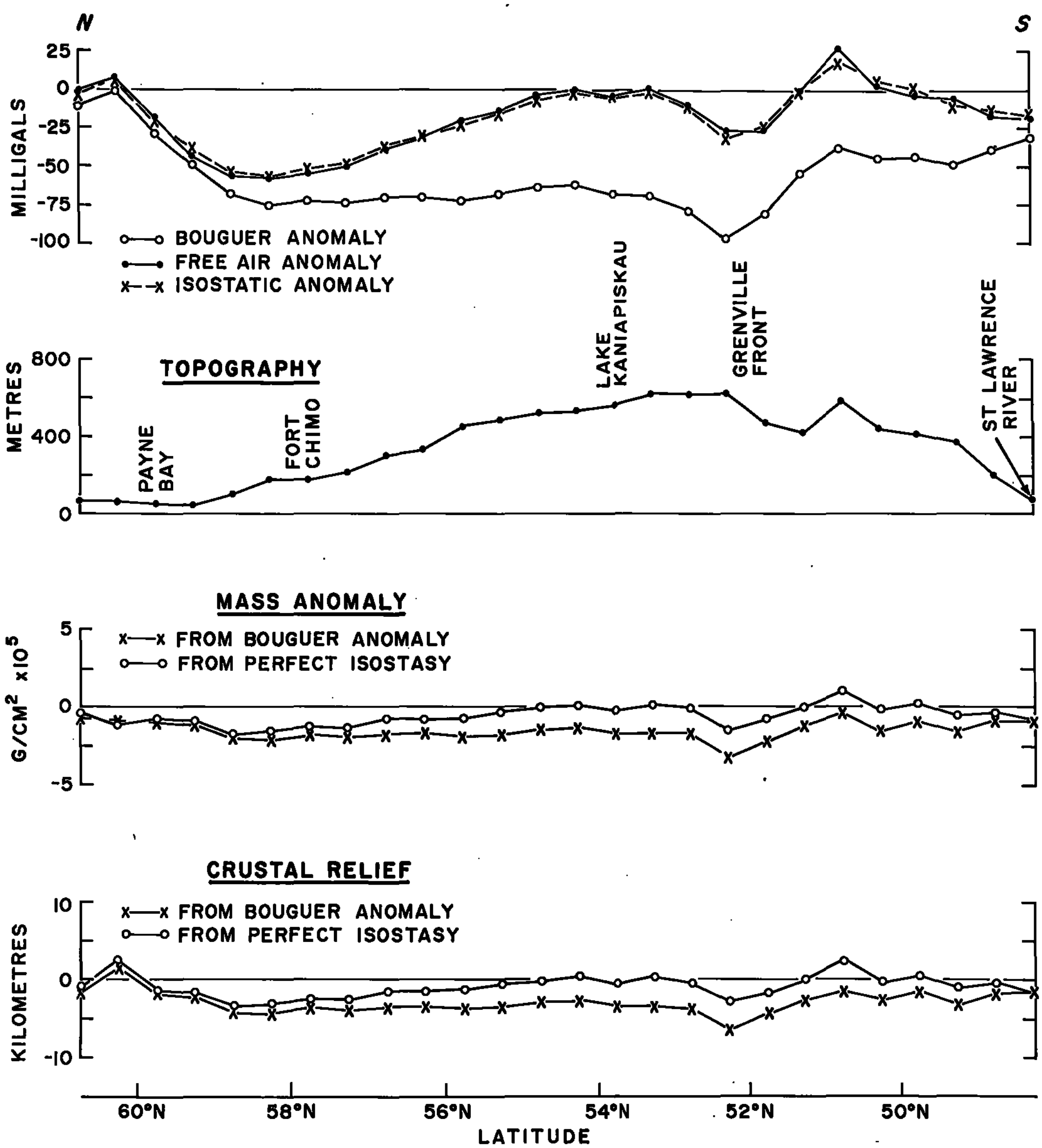


Fig. 4-7

Gravity and isostasy along a north-south profile at the 70th meridian.

over the Labrador Trough is slightly wider than the corresponding anomaly on the regional Bouguer anomaly map. As with the Bouguer map, the linear anomalies over the Cape Smith Belt are not apparent.

In Fig. 4-7 the Bouguer and free air anomalies are shown in comparison to the isostatic anomaly, calculated by the (sin x)/x method for a crust 35 km thick, and the topography along a profile at 70°W. Comparison of the Bouguer and topographic profiles shows again the regional inverse correlation between them. The striking feature of the profile is the remarkable similarity between the free air and isostatic anomalies. The two profiles are the same everywhere except for a small area just to the south of the Grenville Front where the free air anomaly shows positive correlation with a local topographic high. All three profiles show gravity lows in the vicinity Fort Chimo where the profile runs along the western part of the Labrador Trough anomaly.

The area contained between the free air and isostatic profiles and the axis of zero anomaly is about 35% of that contained by the Bouguer profile and, with allowance for the effect of the Labrador Trough anomaly on all three gravity profiles, it can be concluded that the topography along the profile is largely compensated. Confirmation of this result for all of northern Quebec can be obtained by a regression of free air anomaly upon elevation which, for 11,500 stations, gives the following result:

$$\overline{FA} = -35.6 + 0.06\,H \text{ mgal},$$

where H is in metres. The coefficient of H is about one-half that expected on the basis of the Bouguer hypothesis, which assumes that compensation of topography takes place at infinity, and this suggests that the topography of northern Quebec is on average fifty per cent compensated. The large negative intercept of the equation, -35.6 mgal at zero elevation, is due mainly to the fact that Hudson Bay is a regional centre of depression of the gravity field. Since Hudson Bay is also a topographic low, the coefficient of H would be expected to correlate positively with elevation and removal of the regionally negative trend toward Hudson Bay would undoubtedly reduce the coefficient of H. It can therefore be concluded that the gross topography of northern Quebec is largely compensated. It is implicit in this conclusion that the topography in northern Quebec on average varies rather smoothly because areas of more local relief, even if compensated, would produce a more positive correlation with elevation than is observed in northern Quebec.

As an approximation to an isostatic anomaly map, the free air anomaly map of Fig. 4-6 confirms the conclusion of other gravity studies that the central part of the Canadian Shield is overcompensated. On average northern Quebec is about 15 mgal overcompensated. The main cause of overcompensation is probably incomplete isostatic recovery upon deglaciation.

This brief study of the relationship of topography and gravity has also shown the necessity of considering the possible effect of compensation of topography in the Grenville Front area during the geological interpretation of the gravity data.

CHAPTER 5

INTERPRETATION OF ANOMALIES OVER THE STRUCTURAL BOUNDARIES

5-1. Introduction

5-1-1. Compensated Crustal Structures.

In the past regional anomalies with gentle horizontal gradients have often been interpreted in terms of structure at the base of the crust. Negative anomalies have been interpreted to indicate a thick crust and positive anomalies a thin crust. This approach to gravity interpretation has produced something of a paradox in certain areas where seismic data are available. For example, the seismic data in the Appalachians of Canada (Ewing, Dainty, Blanchard and Keen, 1966) indicate that where the gravity anomalies are positive there is a thick crust, a thick intermediate layer and a high crustal velocity and that where the gravity anomalies are negative there is a thin crust, no intermediate layer and a normal or low crustal velocity. In areas where the crust is thick the upper mantle velocity is also high. These results indicate that lateral variations in mean crustal density are compensated by variations in crustal thickness and hence that isostatic equilibrium has been broadly achieved during the development of crustal structure in the Canadian Appalachians. A similar result has been observed in the Lake Superior basin of the Precambrian Shield where seismic studies (Berry and West, 1966) indicate a thick crust in an area where the gravity anomalies are regionally high (Weber and Goodacre, 1966). The joint interpretation of the gravity and seismic data requires that there be a great thickness of basic volcanic rock within the crust in the regions where the crust is thickest (Weber and Goodacre, 1966).

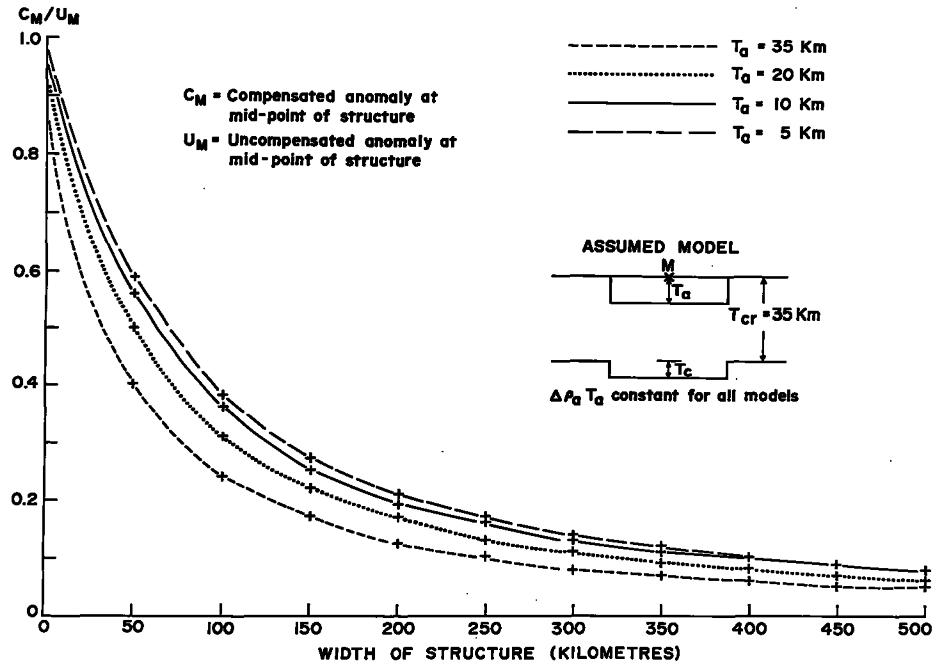
It is usual to think of isostasy in terms of compensation for topography, but it may also apply to the development of anomalous masses within the crust. For example, the intrusion of a large amount of basic material into the crust from the upper mantle creates a problem with respect to the space needed for the basic intrusion and the load due to the intrusion. This would not be a problem if the process of intrusion is accompanied by crustal warping or collapse. After the process, isostatic equilibrium would be largely retained and the end result would be what is termed here a "compensated crustal structure".

Another process that could lead to the development of a relatively thick crust in isostatic equilibrium may result from the combined effects of regional metamorphism, folding and erosion. Strong regional metamorphism tends to subdivide the crust into an upper zone of light granitic rocks and a lower zone of more basic high grade metamorphic rocks. Folding shortens the crust and hence produces a thicker crust. Subsequent erosion gradually removes the upper more granitic rocks to expose a more basic crust. The amount of mass removed during erosion would be less in areas where metamorphic zoning has produced a low density upper crust than in areas where metamorphism either has not occurred or has occurred only mildly. If isostatic equilibrium is maintained during the process then the areas in which strong regional metamorphism has occurred should ultimately be underlain by a thicker crust.

The processes outlined above are undoubtedly oversimplified and ignore the effects of geological processes on the upper mantle. The seismic data in the Appalachians indicate that the velocities in the upper mantle are variable as do the preliminary results obtained from the Grenville experiment (see Chapter 4). While there is good reason to believe that there may be mass variations within the upper mantle, more information than is available for this study in northern Quebec is necessary to include the upper mantle in the gravity interpretation. This is true even in the Grenville region where the results given in Chapter 4 are preliminary and do not include a seismic model upon which the gravity interpretation can be based. The interpretation of the regional anomalies over the structural boundaries will therefore be confined to mass distributions in the crust. This is not regarded as a serious limitation of the interpretation because it will be seen that mass variations in the upper mantle will alter the detail of the interpretation, but will not be likely to affect the hypothesis used for the interpretation.

Since the structural boundaries studied in this thesis separate four major subdivisions of the Canadian Shield in northern Quebec and since there is increasing evidence from seismic and gravity studies for the development of compensated crustal structures, the next section of this introduction will be devoted to the distribution of gravity over such structures. In the discussion emphasis will be placed on the gravity anomaly over the edges of the structures and on the implications of the hypothesis on estimates of the thickness of anomalous masses within the crust.

Fig. 5-1
The gravity effect at the mid-point of compensated structures.



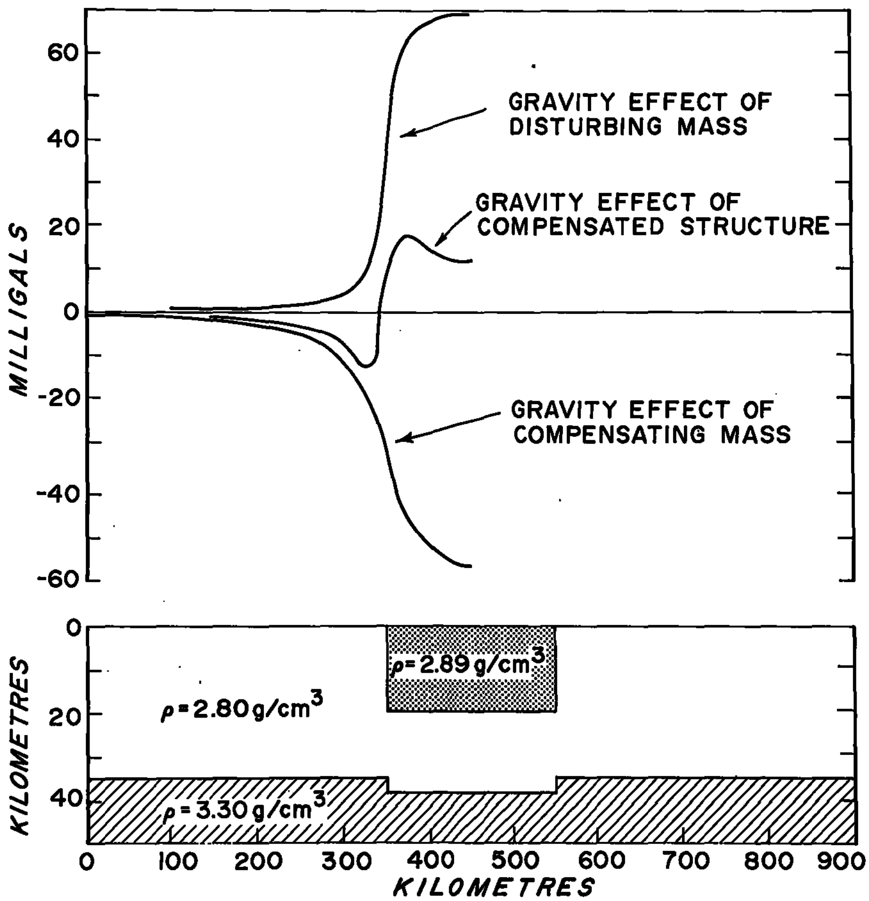


Fig. 5-2
The distribution of gravity over a compensated structure.

5-1-2. Distribution of Gravity over Compensated Crustal Structures.

Fig. 5-1 shows the ratio of the total anomaly due to the compensated crustal structure and the anomaly due to the anomalous mass within the crust at the mid-point of structures up to 500 km in width. The calculations assume that the structures consist of two-dimensional rectangular blocks. The diagram shows that only about 5% of the gravity effect of a compensated structure 500 km wide would be recorded at the surface because the effect of the compensation at depth nearly cancels it out. As the width of the structure decreases the gravity effect of the near surface mass becomes progressively more predominant. For local structures it is readily seen that the effect of compensation could be ignored without serious error in the interpretation.

The gravity anomaly over the margin of a compensated structure is distinctive as can be seen in Fig. 5-2 which shows the anomaly due to a compensated structure 200 km in width. The important features of the anomaly are:

(a) the positive anomaly over the structure,

(b) the negative anomalies flanking the structure,

(c) the steep horizontal gravity gradients over the edge of the block,

(d) the gentle gradients of the outer limb of the flanking negative anomalies.

Although simple block-shaped masses such as are used in the diagram would not be expected in practice, major structural discontinuities between different crustal blocks in isostatic equilibrium could cause anomalies broadly similar to that shown in Fig. 5-2, in which case the character of the profile should provide a strong clue as the nature of the structure causing the anomaly. Obviously additional support for the hypothesis must come from geological, seismic and other relevant geophysical data.

If an anomaly such as that shown in Fig. 5-2 is not interpreted as a compensated structure, it is most likely that the thickness of the near surface structure would be underestimated. The amount by which its thickness is underestimated would vary according to the hypothesis used to interpret the anomaly.

5-1-3. Density Assumptions.

The results of the density measurements have been summarized in Chapter 4 where the problems encountered in obtaining good areal coverage and representative samples were emphasized. It is only in the Cape Smith region that there is adequate information to compile a table of densities. In the Labrador Trough area there are virtually no samples and the interpretation is based on general information obtained from other areas. The Grenville province has been sampled to some extent, but the complex geology of this province has precluded presentation of the results in tabular form.

Because of the limited density measurements available and the problems of classifying them, it has been necessary to assume the density of major rock types involved in the interpretations. The two main types of dense upper crustal rock and their assumed densities are as follows:

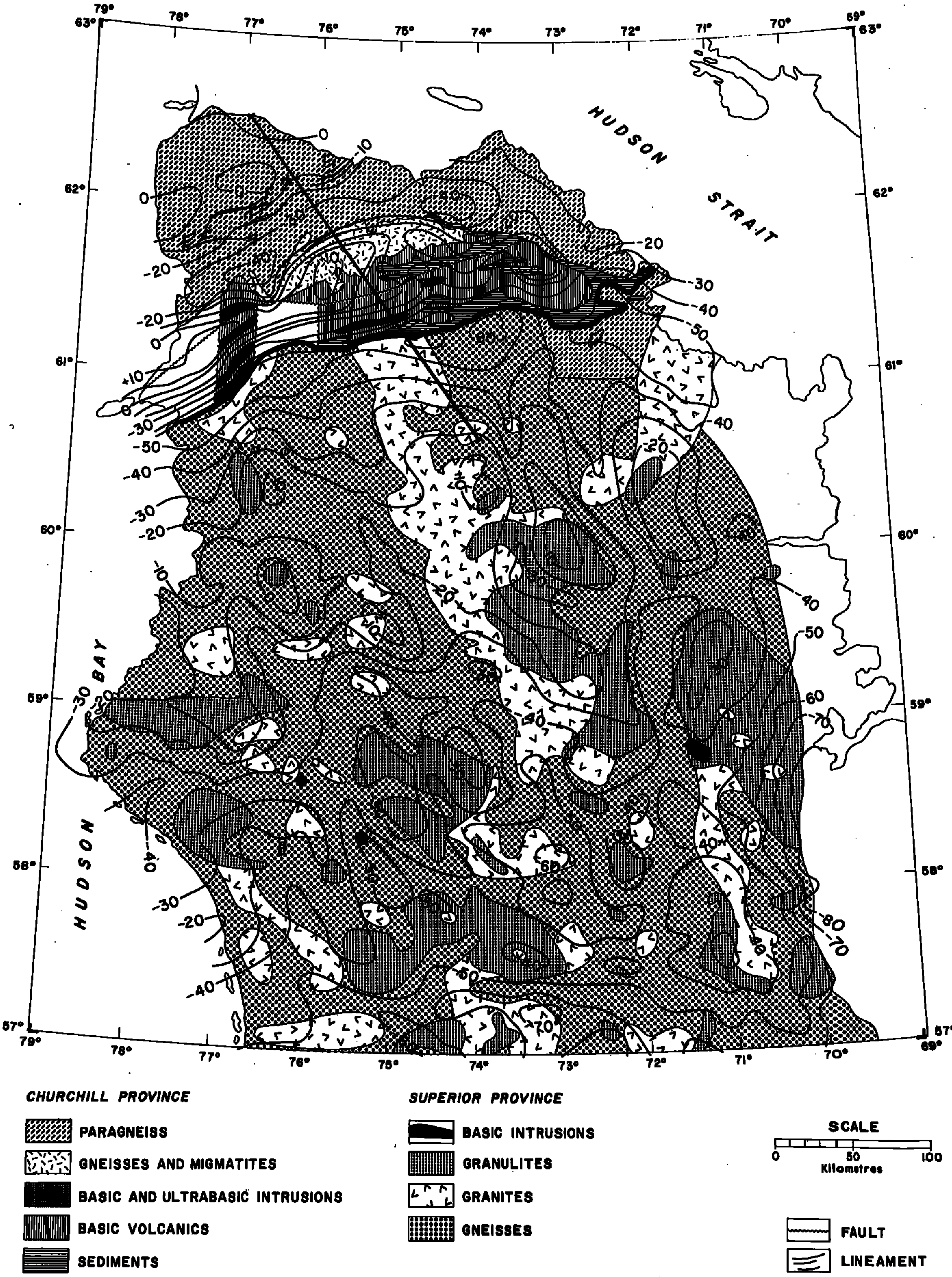
(a) basic extrusive and intrusive rocks - 3.0 g/cm^3,

(b) granulites - 2.8 g/cm^3.

Fig. 5-3

Geology and gravity of the Ungava region. The geological information is based on a preliminary compilation for the region by the Quebec Department of Mines. Gravity units are milligals.

GENERALIZED GEOLOGY OF UNGAVA PENINSULA



The background density for the upper crust is assumed to be 2.7 g/cm^3 and that for the lower crust 2.9 g/cm^3. The upper mantle is assumed to have a uniform density of 3.3 g/cm^3. It is possible that the assumed density at the base of the crust is too low, but this does not seriously affect the interpretation.

In the remainder of this chapter the interpretation of the gravitational field in the vicinity of the Cape Smith Belt, the Labrador Trough and the Grenville Front will be given. Generally only one model will be given for each region, but a discussion of possible alternatives to the interpretations presented will be given in each section.

5-2. The Cape Smith Region

5-2-1. Introduction.

The anomalies over the Cape Smith Belt have been previously interpreted by Tanner and McConnell (1964). Subsequently to their study there has been additional geophysical work carried out within the area. The first of these is the reconnaissance work by Innes et al (1967) in Hudson Bay. This study consisted of a regional correlation of gravity and geology throughout the northern part of Hudson Bay region, including the Ungava Peninsula. The second is the seismic experiment in Hudson Bay from which Ruffman and Keen (1967) suggested structure at the base of the crust at the boundary between the Churchill and Superior provinces. The third and last is a gravity traverse (Fig. 5-3) along the Ungava Peninsula at right angles to the strike of the Cape Smith Belt. This work, which was carried out by the author in 1965, provided gravity measurements and rock samples at 6 km intervals along the traverse. The rock sampling was carried out partly to determine whether there is any systematic decrease of density in the vicinity of the gravity lows flanking the Cape Smith high.

Unfortunately there has been no additional geological mapping in the area and the description of the geology, given next, is essentially that of Tanner and McConnell (1964). The description of the geology is followed by the interpretation of the gravity data.

5-2-2. Geology of the Ungava Peninsula.

Fig. 5-3 shows a generalized map, based on an unpublished compilation provided by Dr. R. Bergeron, Quebec Department of Mines, for the Ungava Peninsula. The southern part of the area is underlain almost entirely by the Archaean granites and gneisses of the Superior province. North of the Superior province are the Proterozoic volcanics, sediments and paragneisses of the Churchill province; the boundary between the two provinces being marked by the southern contact of the Cape Smith Belt. In the remainder of this sub-section the various structural units will be described from the point of view of their relevance to gravity data.

Superior Province: The geological mapping of this northern part of the Superior province has resulted from helicopter operations of the Geological Survey of Canada (Stevenson, 1965) and from geological work carried out in connection with the gravity survey of 1959 (Kretz, 1960). With the exception of the Proterozoic basaltic and sedimentary rocks of the Manitounuk Group on the east shore of Hudson Bay (not shown on map), the rocks exposed here consist mainly of granites and granitic gneisses containing mineral assemblages indicative of the upper range of the amphibolite facies. These rocks are far from homogeneous and contain inclusions of more basic rock and are intermixed to varying degrees with other non-granitic rock. The basic inclusions are variable in size and Kretz (1960) reports the presence of outcrops of basic rock which, when observed from the air, are apparently only very large inclusions. Since the lithology of the units shown in Fig. 5-3 as gneisses and granites respectively is extremely variable, the lithological boundaries between them are approximate and serve only to define areas in which banding and other gneissic structure is more or less pronounced. On this basis a marked density contrast would not be expected between the two units, which is consistent with results obtained from an analysis of about 150 density measurements south of the Ungava region where it has been found that granites are about 0.05 g/cm^3 less dense than the gneisses (Tanner, 1961).

The pyroxene-bearing granodiorites and gneisses have been described by Eade et al (1966) and Eade (1966). These rocks are characteristically medium-grained, rudely foliated, yellowish green in colour and have a greasy lustre. The common minerals of the rock are biotite, quartz, plagioclase, and pyroxene; magnetite and apatite are present as accessories. According to Eade (1966) the presence of biotite indicates that these rocks belong to the lower granulite facies. As indicated in the previous chapter, little is known about the densities of these rocks, but on the basis of results from other areas they would be expected to be more dense than the granitic rocks, but probably only slightly so because of the presence of quartz and biotite.

Small plugs of basic and ultrabasic rocks also occur within the region, but outcrops of these rocks are scattered sparsely throughout the area. These rocks are not of direct significance to the gravity interpretation because of their small area of outcrop and are mentioned here only because they may be related to the event which produced the granulitic rocks.

Throughout the area the dominant strike is north and the dip vertical (Kretz, 1960). Prominent lineaments occur throughout this portion of Superior province; many of these are scarps and therefore probably faults (Kretz, 1960) which may be related to the last tectonic event that affected the Superior rocks, apparently about 2500 my ago. Eade (1966) suggests that this event probably produced the granulite facies metamorphism.

Churchill Province: The Cape Smith Belt has been partially mapped at a scale of an inch to the mile by the Quebec Department of Mines. Although mapping is incomplete, there is sufficient geological data for this regional interpretation. The description given below draws mainly on summaries given by Bergeron (1957), Kretz (1960) and Stam (1961).

The Cape Smith Belt, which varies in width from a maximum of about 90 km in the centre to a minimum of about 15 km at its eastern extremity, is subdivided into two series, an Upper or Chukotat Series and a Lower or Povungnituk Series. The Lower or Povungnituk series consists of sedimentary and altered basic volcanic rocks. The sediments are mainly pelitic schists, but dolomite and quartzites are present locally. Iron formation also occurs within this series, but is apparently restricted to the area of the southern contact in the central part of the Cape Smith Belt. The total thickness of the sediments is not known; estimates varying between 1 and 3 km have been given in the literature. The volcanic rocks of this Lower series consist mainly of pillowed and massive basalt with some andesite.

The Upper or Chukotat Series consists mainly of a great thickness of lava with minor amounts of sedimentary rock. Again the dominant volcanic rocks are massive and pillowed basalts. Beall (1959) estimates that the volcanic rocks of this series are in excess of 5 km thick in the east central part of the belt.

Gabbroic and ultrabasic intrusions occur within both series of rocks. These rocks are broadly concordant and apparently were intruded prior to folding.

The geological map shows a large area of gneissic rock outcropping in the northern part of the Cape Smith Belt. Little information is available on this unit, but according to Gelinas and Bergeron (1962) the rocks are probably metamorphosed quartz diorite and granodiorite. It is not known whether the rocks of this unit underlie or cut the volcanics and sediments.

Beall et al (1963) have suggested, from radiometric studies, that tectonic activity within the belt began about 2400 my ago and terminated about 1400 my ago with the greatest orogeny within the belt occurring at 1600 my. The structural development of the area cannot be considered independently of that of the north-south striking Labrador Trough which developed approximately contemporaneously with the Cape Smith Belt.

As might be expected from the history of events throughout the region' the structure of the Cape Smith Belt is complex. The most prominent structural feature is a major thrust fault, located near the axis of the belt, which can be traced throughout the length of the belt. In addition, Stam (1961) has mapped several thrust faults in the western part of the belt, all of which appear to dip north at an angle of 30°. Structures transverse to the strike of the belt, such as faults, cross-folds and basin and canoe-shaped folds, are common and may be related to events occurring within the Labrador Trough.

The nature of the contact between the Cape Smith Belt and the gneisses and granites of the Superior province to the south has not been definitely established. Bergeron (1957) suggests that it is an unconformity; Kretz (1960) and Stam (1961) believe it to be a thrust fault. Bergeron (1957) gives the only reference to the nature of the northern contact, which he crossed in one locality only. He suggests that it is gradational.

<u>The paragneisses</u> to the north of the Cape Smith Belt have been described by Kretz (1960) as heterogeneous gneisses and migmatites. These main structural trends in this area are easterly and dips apparently northward.

<u>Densities:</u> A summary of all density measurements in the Ungava region is given in Table 5-1. The volcanic and sedimentary rocks of the Cape Smith Belt have not been separated in the table because of insufficient data. The few density measurements that have been made on the sediments indicate that their density is roughly the same as that for the gneisses and granites of the Superior province. There are undoubtedly density measurements on the granulites included in the broad category of gneisses and granites because these rocks and their possible significance had not been recognized at the time of the surveys.

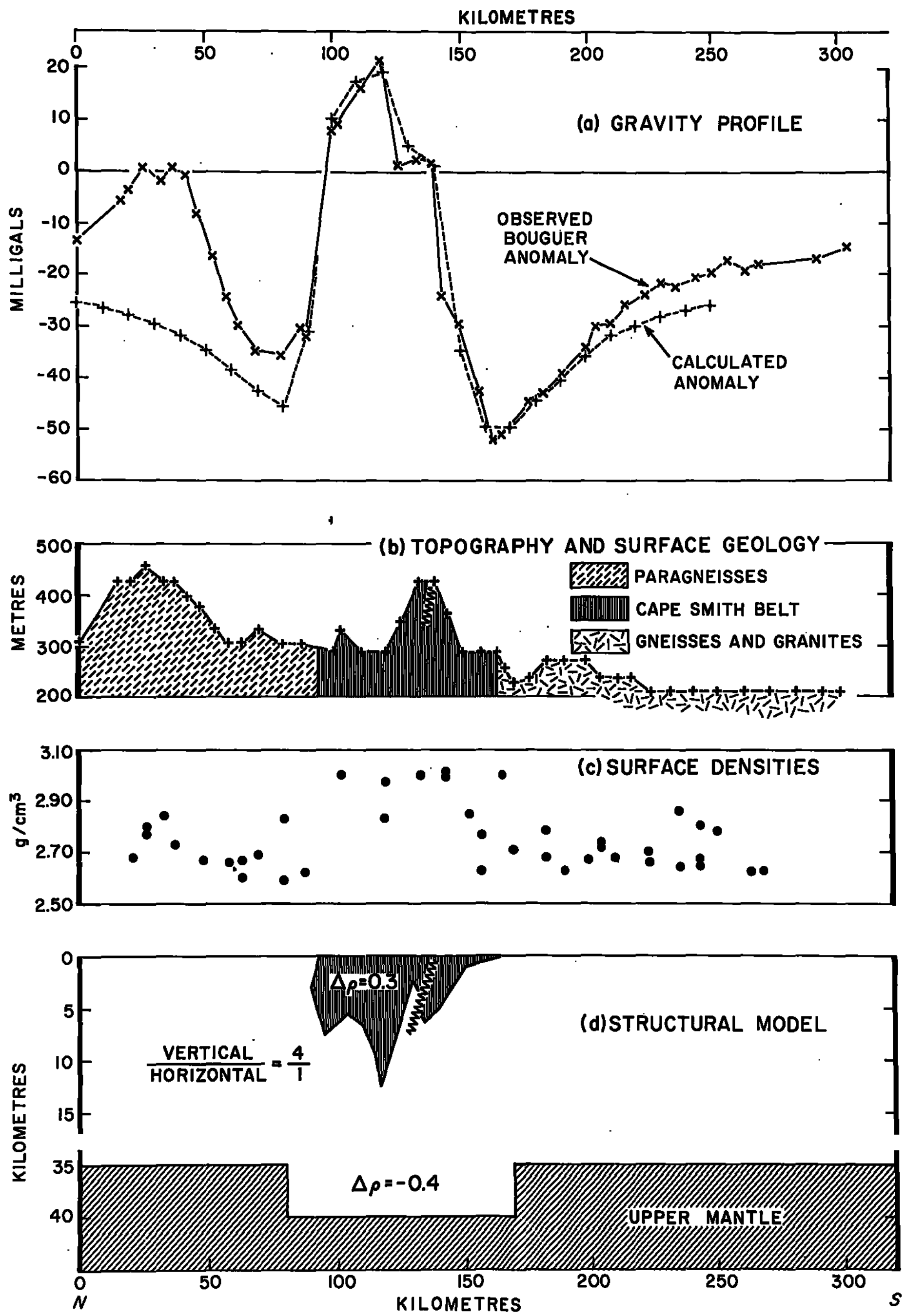


Fig. 5-4

Interpretation of the Cape Smith anomaly. The geology has been taken from a preliminary map provided by the Quebec Department of Mines Topography scaled from maps at a scale of 1:250,000.

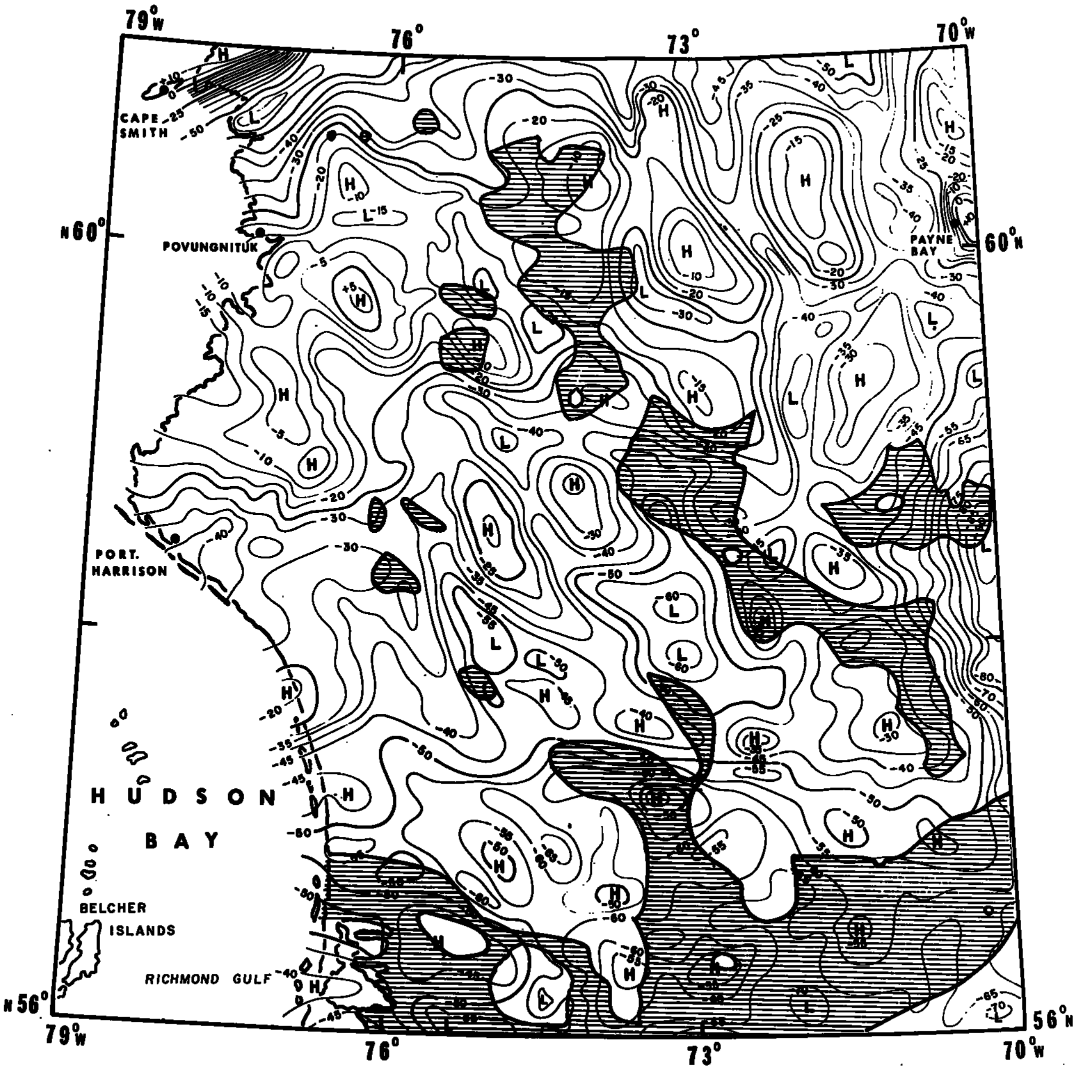
TABLE 5-1

DENSITY MEASUREMENTS IN THE UNGAVA REGION

Geologic Geologic Unit	No. of Samples	Mean Density g/cm^3	Standard deviation g/cm^3	Range of Density g/cm^3
Paragneisses of Churchill province	30	2.75	±0.15	2.56 - 3.08
Sedimentary and volcanic rocks of Cape Smith Belt	40	2.96	±0.14	2.62 - 3.15
Basement gneisses and granites of Superior province	70	2.70	±0.13	2.44 - 3.24

5-2-3. Interpretation of the Cape Smith Anomalies.

The Bouguer anomaly field is shown in Fig. 5-3 as an overlay to the geological map and in Fig. 5-4 along a profile taken at approximately right angles to the strike of the Cape Smith Belt. Also shown in Fig. 5-4 are the topography, surface geology and surface densities. The main features of the gravity profile in Fig. 5-4 are the large positive anomaly over the Cape Smith Belt which reaches a maximum of about 20 mgal near the axis of the belt and the negative anomalies flanking the Cape Smith Belt. The southernmost negative anomaly reaches a minimum of about -50 mgal over the southern contact of the Cape Smith Belt. The northernmost negative anomaly has a minimum value of about -35 mgal approximately 20 km north of the Cape Smith Belt. The other distinct anomaly on the map is the gravity high over the paragneisses which reaches a maximum of zero anomaly about 60 km to the north of the Cape Smith Belt.



L E G E N D

Granite, quartz monzonite, granodiorite, diorite, pegmatite. Massive to poorly foliated; may contain pyrobole fragments

Other rocks

—-50— Contour of equal Bouguer anomalies at intervals of 5 milligals

—— Geological boundary

Scale 0 100 km

Fig. 5-5
The relationship of the Bouguer anomaly field to granitic rocks in the Ungava Peninsula. Gravity units are milligals.

This interpretation will concentrate on the positive and negative anomalies near the Cape Smith Belt. For the interpretation it will be assumed that the lows to either side of the Cape Smith high have a common source. The structural model which is believed to explain the anomalies best is given in Fig. 5-4. At the completion of the Cape Smith interpretation a qualitative discussion of the gravity field away from the Cape Smith region will be given.

Cause of the Cape Smith Anomalies: The steep horizontal gradients of the Cape Smith high leave little doubt that it is caused by the basic volcanic and intrusive rocks outcropping in the belt. Of these it appears that the volcanic rocks are probably the main source of high gravity anomalies for two reasons:

(a) the volcanic rocks are known to be at least 5 km thick near the axis of the belt,

(b) the intrusions mapped at the surface are usually small lenticular bodies that are concordant with the structure of the volcanic rocks.

The cause of the gravity lows is not obvious from the surface geology. The sediments in the Cape Smith Belt cannot be the major cause of the gravity lows because the areas of low gravity extend well beyond the limits of outcrop of the Cape Smith Belt. This leaves granitic intrusive rocks and structure at depth as other possible causes of low gravity.

The granites of the Superior province are shown in Fig. 5-5 in relation to the Bouguer anomaly field. Examination of this diagram shows there is very little correlation between the granites and Bouguer anomaly which would indicate that either these rocks are thin or the density contrast between the granites and the other rocks is not significant. A combination of both is, of course, always possible. A similar result has been observed by Tanner (1961) to the south of the Ungava Peninsula where outcrops of granitic rocks, while more abundant, cause small anomalies only. Other factors which suggest that the negative anomalies are not caused by granitic intrusions are:

(a) the density measurements along the profile (Fig. 5-4) do not show any systematic decrease toward the Cape Smith Belt,

(b) the dominant structural trend within the Superior province south of the Cape Smith Belt is apparently north-south (Kretz, 1960),

(c) anomalies due to granitic intrusions are usually much more irregular than those in the Cape Smith region - a good example of this can be seen in the southwest portion of the Bouguer anomaly map (in pocket) where the east-west trending granitic belt of the Kirkland Lake mining region causes an irregular pattern of anomalies.

Granitic intrusions are therefore, not considered a likely cause of the regional negative anomalies.

The southern half of the profile in Fig. 5-4 is similar to that for a structure compensated at the base of the crust (Fig. 5-2). Since structure at the base of the crust produces a broad regional negative anomaly, this hypothesis would require that the locally high gravity field over the paragneisses north of the Cape Smith Belt is caused by an independent shallow structure.

The existence of a thick crust under the Cape Smith Belt appears reasonable on the basis of the geology which indicates that a great thickness of basic volcanic rocks have been extruded within the belt. The addition of such a load on the crust could be expected to cause crustal warping or collapse in compensating for the load. Some support for this hypothesis comes from the seismic results in Hudson Bay (Ruffman and Keen, 1967) which indicate that the crust thickens under the presumed extension of the Superior-Churchill boundary into Hudson Bay.

The structural model shown at the bottom of Fig. 5-4 has been computed on the basis that the positive anomaly over the Cape Smith Belt is caused mainly by basic volcanic rocks and that the gravity field in the area is regionally depressed due to crustal warping.

Shape and Structure of the Cape Smith Belt: The computations have been made assuming that the density contrast between the basic volcanic rocks of the Cape Smith Belt and the surrounding rocks is 0.3 g/cm^3, but other density contrasts could provide an equally good fit to the gravity data. However, it does not seem that a density contrast lower than about 0.2 g/cm^3 could satisfy the gradients on the margins of the observed anomaly.

In Fig. 5-4 the Cape Smith Belt is shown as a broadly folded, inward dipping structure reaching a maximum thickness in excess of 10 km along the axis of the belt. The thrust fault shown in the diagram corresponds to the major thrust fault which, in plan view, extends the length of the Cape Smith Belt. This fault has been included in the interpretation to explain the local depression in the profile just to the south of the apex of the Cape Smith high. The relative vertical movement along the fault indicated by the gravity interpretation is about 2 km. As an alternative to the model shown, the observed anomaly could be explained by showing the profile of the Cape Smith Belt as a series of thrust faults as suggested by Stam (1961).

The downward protrusion shown near the axis of the belt may be a relict of the sag structure caused by the emplacement of the lavas. In addition to being required as part of the explanation of the anomaly, a structure such as this would seem essential because of the large volume of volcanic rocks that have obviously been extruded. The only alternative to this interpretation would be to postulate a large basic intrusion within the belt, but this would not seem likely because of the small size of the intrusions exposed within the belt.

In the structural model of Fig. 5-4 the northern contact of the Cape Smith Belt dips northward at a high angle whereas the southern contact dips northward at a shallow angle. A steeply dipping northern contact and a shallow dipping southern contact are required because of the horizontal position of the contacts with respect to the observed anomaly. The northern contact is located at a point where the anomaly reaches approximately half its maximum value and this relationship requires that the dip of the contact is nearly vertical. Conversely, the southern contact is located at a point where the observed anomaly is near zero which requires that the dip of this contact is shallow and inwards.

By comparison with the dips indicated by the gravity data, the dips measured at the surface average about 30° north near the southern contact and 50° south near the northern contact of the Cape Smith Belt. The difference may be explained by the presence of local structures within the belt which would not be detected by gravity observations spaced at intervals of approximately 6 km.

It will be recalled that geologists have not agreed whether the southern contact of the Cape Smith Belt is a thrust fault or an unconformity. Since the other thrust faults in the belt are reported to dip 30° or more northward, it is possible that the shallow dip angle determined from the gravity interpretation indicates an unconformity. It is even possible, as King (1951) has suggested in the Appalachians, that the contact was originally an unconformity which subsequently served as a locus for thrusting.

The sediments of the Cape Smith Belt are largely an unknown quantity in the interpretation because the absence of a density contrast between the sediments and the granites and gneisses of the Superior province has not been definitely established. Since the sediments lie at the base of the sequence in the Cape Smith Belt, large variations in their thickness would change the shape of the structure considerably from that shown in Fig. 5-4. The only suggested distribution of sediments is that of Stam (1961) who shows them diagrammatically as a fairly thin layer at the base of the succession.

The gravity data also provide a clue to the nature of the gneisses and migmatites which outcrop within the belt north of the major thrust fault. It will be recalled that Gelinas and Bergeron (1962) stated that it had not been established whether these rocks intrude the volcanic rocks or represent the basement. It is clear from the gravity data that these rocks could not possibly represent basement and that if they intrude the volcanics, they are minor because their effect on the Bouguer anomalies is negligible. It might be more in agreement with the gravity data to regard these rocks as a thin, erosion-reduced remnant of overlying metamorphic rocks.

The final comment on the gravity data over the Cape Smith Belt concerns the relationship of the gravity field (Fig. 5-3) to the areas within the belt where the development of structures transverse to its strike are most pronounced. The gravity map in Fig. 5-3 shows that the gravity field pinches in two places. These occur where the development of cross structures is reported to be most prominent. This could mean that the Cape Smith Belt is thinner in these areas than elsewhere. There is also a suggestion from the gravity map that these trends over the Cape Smith Belt may extend into the areas adjacent to the belt. If this is true then the presence of trends in the gravity field which extend across the Cape Smith Belt into the Superior province which are parallel to the strike of the Labrador Trough may indicate that the Superior province was affected by an orogeny which took place in the Proterozoic.

<u>Structure at the Base of the Crust:</u> It is assumed in the model shown in Fig. 5-4 that the anomalous mass causing the Cape Smith low is concentrated at the base of the crust. The source of the anomaly could be placed at a shallower depth and it is also possible to ascribe the cause of the anomaly jointly to sources both within and at the base of the crust. Since there is no evidence from the

seismic results in Hudson Bay for a density discontinuity within the crust, it is an unnecessary complication to present an interpretation involving structure within the crust.

In Fig. 5-4 the computed thickness of the structure at the base of the crust is about 5 km. Perfect isostasy requires that the load of the near surface material is balanced by the buoyant force due to the root at the base of the crust. This condition leads to an expression for the thickness of the root at the base of the crust as a function of the thickness of the near surface mass and the densities of the near surface mass, the upper and lower crust and the upper mantle. The formula is

$$\Delta T = T_a \; (\rho_a - \rho_{uc})/(\rho_m - \rho_{1c}) \quad ,$$

where T_a is the thickness of the anomalous mass, ρ_a is the density of the anomalous mass, ρ_m the density of the upper mantle, ρ_{uc} the density of the upper crust and ρ_{1c} the density of the lower crust. On the assumption that $T_a = 5$ km, $\rho_a = 3.0$ g/cm^3, $\rho_{uc} = 2.7$ g/cm^3, $\rho_{1c} = 2.9$ g/cm^3 and $\rho_m = 3.3$ g/cm^3, the crustal thickening (ΔT) is estimated to be about 4 km. This calculation is in reasonable agreement with the results obtained in the model studies of Fig. 5-4.

Ruffman and Keen (1967) have suggested that crustal thickening under the Ottawa Islands corresponds to the extension of the Churchill-Superior boundary into Hudson Bay. They calculate from the seismic data that the crustal thickening is about 12 km. The regional change of anomaly over the boundary in the Ungava Peninsula is about 45 mgal and a similar change of anomaly over the Ottawa Islands would require that the density contrast at the base of the crust is between 0.1 and 0.2 g/cm^3. While a reasonable fit to the regional anomaly could be obtained at these density contrasts, there is a problem with regard to the nature of the rock at the base of the crust. Basic rocks do not usually have densities as great as 3.2 g/cm^3 and most unaltered ultrabasic rocks usually have a density of about 3.3 g/cm^3 which is the density assumed for the upper mantle in this study. Either there is very unusual rock at the base of the crust or there are velocity variations within the crust affecting the seismic determination of crustal thickness.

Discussion of Anomaly over Paragneisses: At the northern end of the profile in Fig. 5-4 there is a residual positive anomaly, which reaches a maximum Bouguer anomaly of zero about 60 km north of the Cape Smith Belt. The density measurements shown in the diagram suggest that the surface rocks near the axis of the anomaly are about 0.1 g/cm^3 more dense than rocks in adjacent areas. This is the density contrast that might be expected from highly metamorphosed rocks, which suggests that the anomaly could be caused by an anticlinal structure or an upthrust block of high grade metamorphic rocks.

Innes et al (1967) have shown that the area of high gravity over the paragneisses extends well to the north and west of the Ungava Peninsula. They suggest that the cause of this huge area of positive anomaly is high grade metamorphic rocks, but they do not exclude the possibility of local accumulations of buried volcanic rocks as a partial cause of the anomaly.

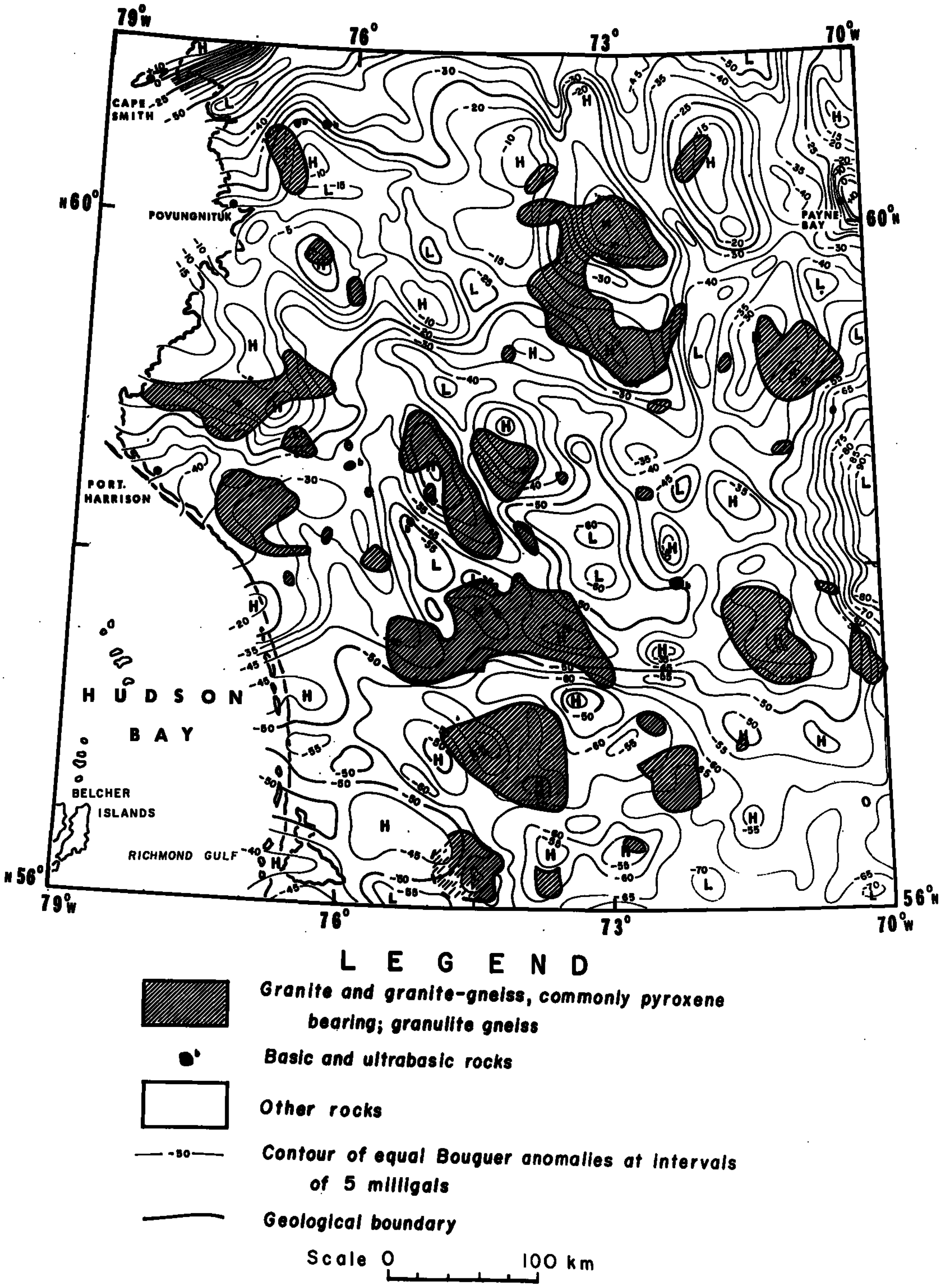


Fig. 5-6
The relationship of the Bouguer anomaly field to granulites in the Ungava Peninsula. Gravity units are milligals.

<u>The Granulites of the Superior Province:</u> Fig. 5-6 shows the gravity field in relation to the known occurrences of granulites in more detail than is given in Fig. 5-3. This area of granulites has been described by Eade et al (1966) as the largest area of granulites in the world.

South of the Cape Smith region the Bouguer anomaly field becomes irregular, but rises to an ill-defined approximately east-west axis of maximum anomaly about 150 km to the south of the Cape Smith Belt. The value of the Bouguer anomaly along this axis varies from about zero anomaly in the west to -15 mgal near the Labrador Trough to the east. South of this axis the Bouguer anomaly field is still irregular, but the regional level of anomaly gradually falls off to a level of about -60 or -70 mgal at approximately 56 N. In the Superior province to the south of this latitude the Bouguer anomaly field is much smoother than in this northern part of the province.

Correlation of gravity with the distribution of granulites is remarkable. Nearly every local gravity maximum shown in Fig. 5-6 is located either directly over or very near to an area of granulites. This excellent correlation between high gravity and surface exposures of granulites suggests that the regionally high values of gravity in this northern part of the Superior province can be explained by the presence of the "layer" of granulites. The existence of a granulite layer in this region raises the question of its possible continuation to the north and south. In this context Eade (1966) has mapped granulites in the area to the south, but has suggested that these may be due to local effects. Although this conclusion might not favour the idea of a continuous layer of granulite under the

Superior province, the hypothesis should perhaps not be discarded completely because Eade et al (1966) have emphasized that the entire area has undergone regional metamorphism which, in the Ungava region of the Superior province, produced a considerable amount of rocks in the granulite facies that are now exposed at the surface. Elsewhere within the Superior province the granulite facies exists locally; the remainder of the rocks belong to the amphibolite facies (probably to the middle and upper part). It is possible that the presence of the granulite facies locally may indicate a more widespread granulitic domain at greater depth.

The suggestion of a "granulite layer" is not novel. In fact, Beloussov (1966) has indicated that Russian seismologists have apparently identified such a layer with the Conrad discontinuity. In the discussion of his paper he indicated that the evidence for this comes from seismic studies which have traced the upper surface of granulites outcropping in the Kola Peninsula down to the Conrad discontinuity. Gibb (1968) has also speculated upon the possibility of a granulite layer at shallow depth in the area of the Nelson River gravity high which marks the boundary between the Churchill and Superior provinces in northern Manitoba.

The gravity map in Fig. 5-6 shows that there is a distinct difference in the character of the anomaly at the northern and southern margins of the main region of granulites. In the south the local anomalies gradually die out southward in an irregular fashion as might be expected for anomalies which have a shallow source. By comparison the Cape Smith low, which marks the northern limit of the granulite region, has uniformly small gradients which means that, if the anomaly has a shallow source, the structure is unusually regular. The existence of a layer of granulites in the Ungava Peninsula remains a matter of speculation, but if proven to exist it would likely only affect the detail and not the principle of the interpretation.

5-2-4. Summary of Cape Smith Interpretation.

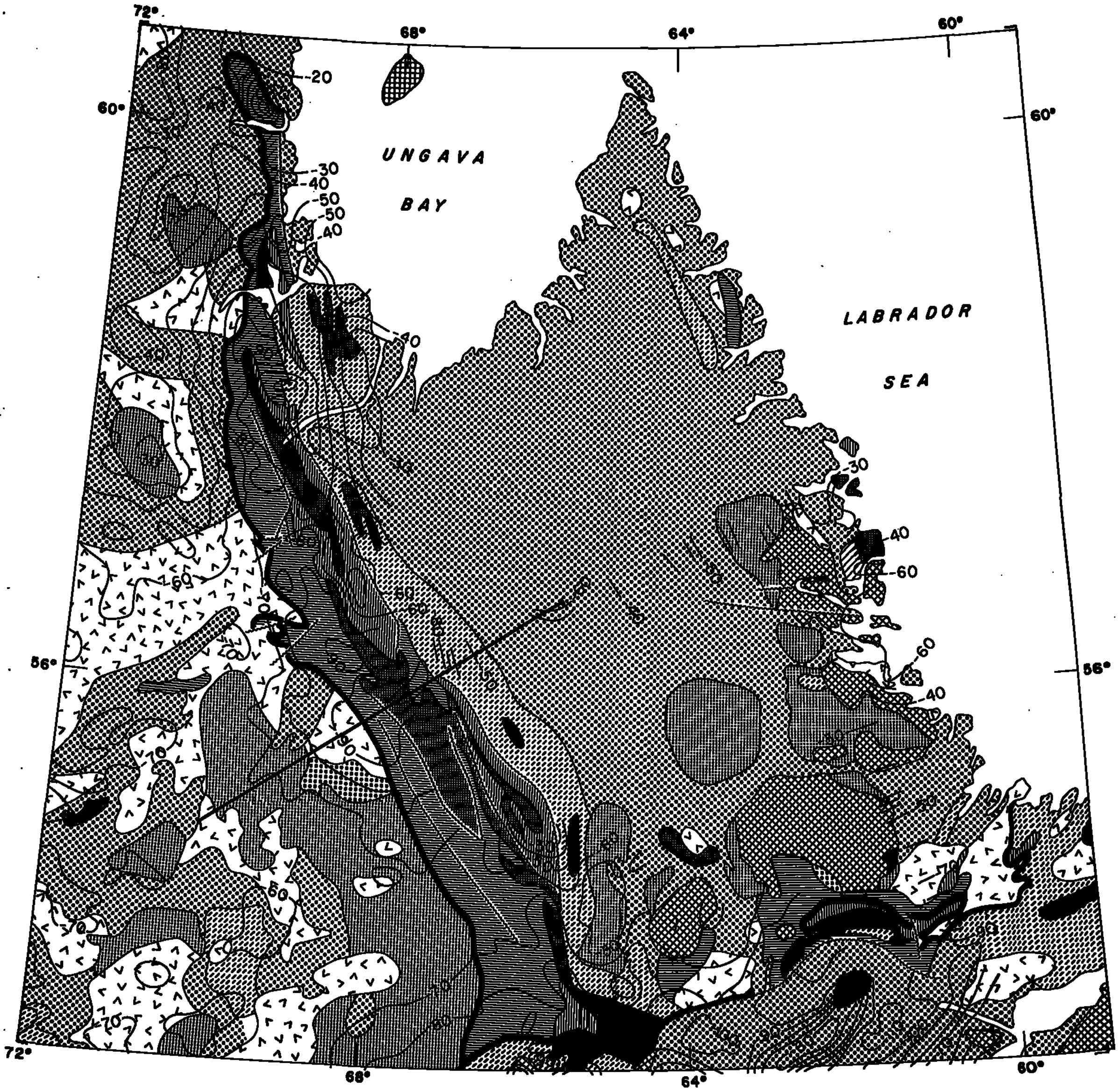
This interpretation has shown that the gravity anomalies over the Cape Smith Belt can be explained by a compensated crustal structure. The compensation is assumed to have taken place at the base of the crust as a result of warping or faulting associated with the extrusion of an enormous thickness of basic lavas. Regionally high Bouguer anomalies north and south of the Cape Smith Belt may be caused by high grade metamorphic rocks. The widespread occurrence of these rocks raises the question of a possible granulite layer.

The folded sedimentary and basic volcanic rocks of the Cape Smith Belt are estimated to be up to about 12 km thick. This result can be compared with those obtained by Grant, Gross and Chinnery (1965) and Innes (1960) for Archean sedimentary and volcanic belts (greenstones) in the Superior province in western Ontario. Grant et al estimate that the Red Lake greenstone belt has a maximum thickness of about 8 km and Innes concludes that other greenstone belts in the area have maximum thickness of 4-6 km or perhaps more. Although these latter are older than the Cape Smith Belt, it would seem that enormous accumulations of basic volcanic rocks have been a feature of the development of the Canadian shield.

Fig. 5-7

The geology and gravity of the Labrador Trough region. Geology after Douglas (1969). Gravity units are milligals.

GENERALIZED GEOLOGY OF LABRADOR TROUGH REGION



PALAEOZOIC SEDIMENTS
PARAGNEISS
ANORTHOSITE
GABBROIC AND RELATED INTRUSIONS
BASIC VOLCANICS
SEDIMENTS
GRANULITES
GNEISSES
GRANITES
FAULT

SCALE
0 50 100
Kilometres

5-3. The Labrador Trough Region

5-3-1. Introduction.

Since the gravity mapping to the east of the Labrador Trough has not been completed, it is necessary to base this interpretation largely on the results of an east-west traverse extending from within the Superior province to the Labrador Coast. For this reason the interpretation will be confined to the immediate area of the Labrador Trough.

5-3-2. General Geology.

As the description of the geology for the Labrador Trough given in Chapter 4 was fairly complete, only a brief review need be given here. This will be done in the context of the relationship of the Trough to the geological units to the east and west of this fold belt (Fig. 5-7).

Superior Province: The rocks of the Superior province underlie the area to the west of the Labrador Trough and are similar to those described for the area to the south of the Cape Smith Belt. The interesting observation with regard to the Superior province is the increased occurrence of granulites adjacent to the fold belt. Granulites are believed to form at depths of about 10 km or more and their high position in the crust adjacent to the fold belt might suggest some relationship to the Trough orogeny. However, radiometric dating in the Superior province indicates that the granulites have an age of about 2500 my which is older than the major orogeny of the Labrador Trough. Since K-Ar dates are usually interpreted to indicate the time of the last orogeny, the age dating indicates that the granulites were not distorted to any extent during the Trough orogeny. Eade (1966) has suggested these granulites were elevated during vertical movements associated with the early development of the Labradorian basin.

Labrador Trough: The Labrador Trough has been described as a fold belt, about 800 km long and 80 km wide, consisting of a western sedimentary section and an eastern igneous section.

The sediments of the trough consist of quarzite, slates, dolomites, chert-breccia and iron formation. The sedimentary strata generally wedge out westward (Harrison, 1952) which suggests that the source of the sediments was to the east. Fahrig (1957) has suggested the following tectonic sequence as an explanation of the development of the sedimentary section:

(a) rapid downwarp and marine transgression,

(b) gradual filling of the basin by sedimentation,

(c) gradual downwarp, marine transgression and extensive deposition of slates.

Fahrig suggests that this sequence of events, with minor modifications, prevailed throughout the length of the Labrador Trough.

The igneous rocks, occurring in the eastern half of the Labrador Trough, consist of basalt, gabbro, basic pyroclastics, and minor intermediate and extrusive rocks. Volcanism probably began in the early history of the Trough and continued throughout most of its development (Fahrig, 1957). The basic intrusions, emplaced prior to folding (Bergeron, 1957), occur mainly as sills ranging up to a kilometre in thickness.

The contact between the rocks of the Trough and those of the Superior province is unconformable, although locally faults are present. This contact appears to dip eastward at a shallow angle of about 10-20°. The area of the eastern contact, as well as being marked by increased metamorphism, is also a zone of pronounced thrust faulting. The direction of thrust faulting is from the east and the tectonic forces which caused these faults also produced numerous anticlines and synclines which are overturned towards the west and southwest.

The Labrador Trough is believed to have been active during the interval 2400-1400 my (Beall,et al, 1963) with the major orogeny taking place at about 1600 my. de Romer (1956) and Bergeron (1957) regard the Labrador Trough as a foothill to the metamorphic complex to the east; the boundary between them is the zone of thrusting mentioned above. They also regard the sedimentary or western portion of the Labrador Trough as miogeosynclinal and the igneous or eastern portion as eugeosynclinal.

Eastern Metamorphic Complex: East of the Labrador Trough the exposed rocks are shown as gneisses, granites and intrusive rocks. Knowledge of this region is limited to results of early reconnaissance surveys of the Geological Survey of Canada. According to Dr. F.C. Taylor (Geological Survey of Canada, personal communication), the widespread occurrence of granulites in the region has not been recognized. However, the rocks in this area appear similar to the granulites found in the Grenville province and have a higher grade of metamorphism than granulites mapped in the Superior province to the west. The presence of numerous anorthositic and basic intrusions in this area to the east of the Labrador Trough also represents another point of similarity with the Grenville province, although it is not known whether these occur on the same scale here as in the Grenville. Archaean rocks are exposed on the coast of Labrador and these are thought to be granulites.

Support for the suggested presence of high grade metamorphic rocks to the east also comes from detailed investigations within the Labrador Trough. Both Fahrig (1957) and Bergeron (1957) have drawn attention to the progressive eastward increase of metamorphic grade across the eastern boundary of the Labrador Trough. At a distance about 30 km east of the Labrador Trough, Fahrig reports metamorphism in the upper amphibolite facies.

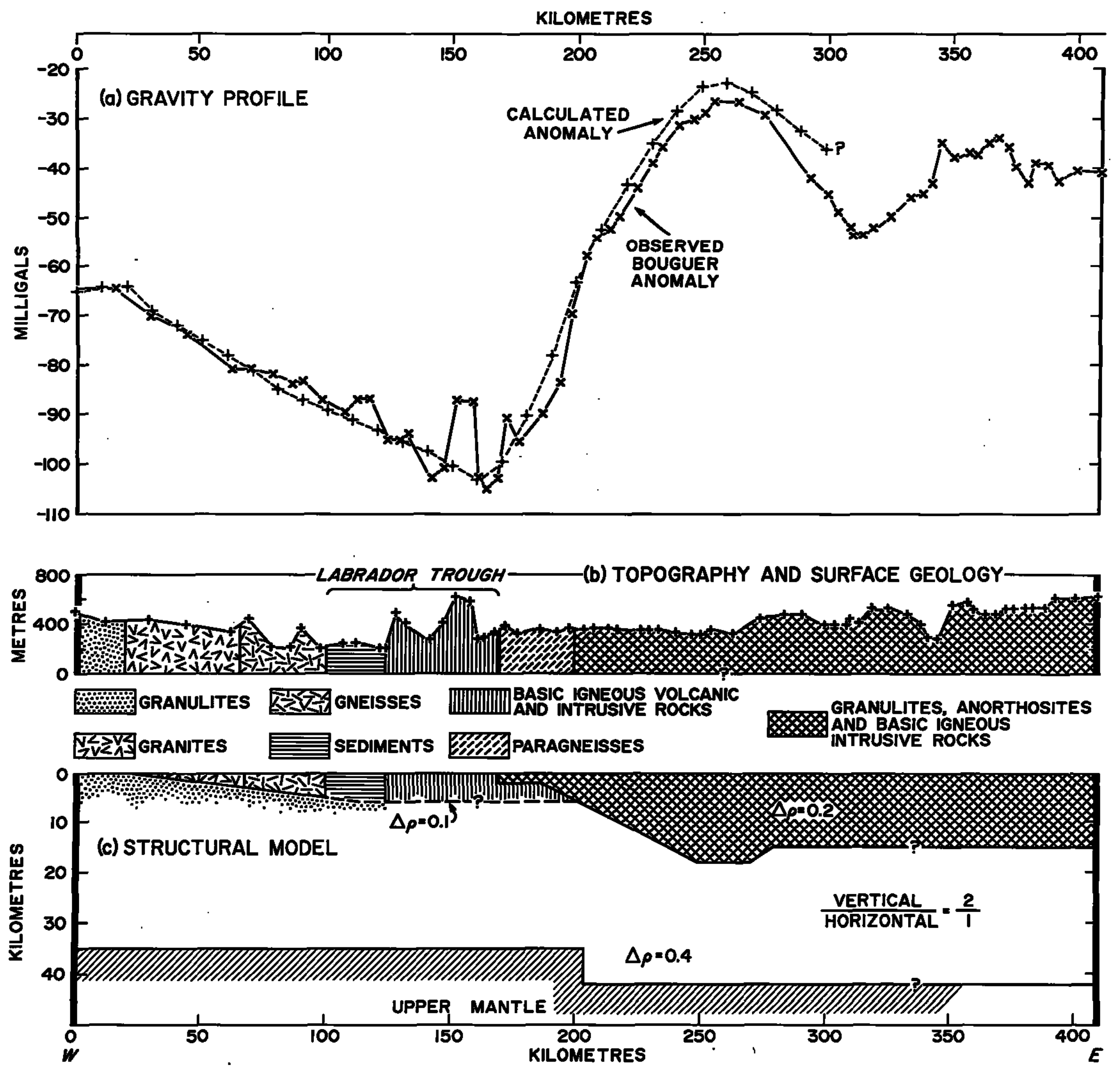
5-3-3. Interpretation of the Labrador Trough Anomaly.

The Bouguer anomaly field is shown in Fig. 5-7 as an overlay to the geological map. Over the Superior province the gravity field is fairly smooth south of about 57°N and more irregular north of this latitude where local positive anomalies occur over outcrops of granulites. The level of the Bouguer anomaly field gradually increases from about -70 mgal to the south to about -30 or -40 mgal to the north within the Superior province.

The dominant feature on the gravity map is the broad regional negative anomaly over the Labrador Trough. This anomaly extends from about latitude 58°N southward for a distance of about 400 km. Generally this anomaly is fairly smooth, but local positive anomalies, which correlate with exposures of basic rocks in the Labrador Trough, occur within it. Minimum values of the Bouguer anomaly are less than -90 mgal and these occur in several places along the axis of the anomaly.

East of the Labrador Trough the only data available consist of an east-west traverse extending to the coast of Labrador and regional stations along the southern shore of Ungava Bay to the north and in the Michikamau Lake area to

Fig. 5-8 Interpretation of the Labrador Trough anomaly. Geology is after Eade, Stevenson, Kranck and Hughes (1960) and Gross (1961). Topography scaled from maps at a scale of 1:250,000.



the south. The observations over the central and northern portions of the eastern metamorphic complex suggest that the Bouguer anomaly field is more positive than generally observed elsewhere within the map area. The maximum anomaly observed is about -25 mgal along the east-west profile.

In Fig. 5-8 a Bouguer anomaly profile across the southern part of the Labrador Trough anomaly is shown in relation to the surface geology and the topography. From west to east the anomaly gradually decreases from a level of about -65 mgal at the western end of the profile to a minimum value of about -100 mgal over the eastern boundary of the Labrador Trough. East of the Labrador Trough the Bouguer anomaly rises rather sharply to a maximum anomaly of about -25 mgal within a distance of approximately 80 km. Further to the east the Bouguer anomaly drops off to a value of -50 to -55 mgal and then rises again to reach a level between -30 and -40 mgal.

The rocks to the east of the Labrador Trough are classified in Fig. 5-8 as a complex of granulites and anorthositic intrusive rocks. This differs from the classification shown in Fig. 5-7 where the complex is shown as consisting of gneisses and igneous rocks. The change in classification has been made in Fig. 5-8 on the basis of personal communication by Dr. F.C. Taylor of the Geological Survey of Canada.

Cause of the Anomaly: One possible cause of the negative anomaly could be the rocks of the Labrador Trough. However, there are three reasons why these rocks are unlikely to be the major cause of the anomaly. These are:

(a) the eastern half of the Labrador Trough is composed primarily of basic igneous rock,

(b) the rocks of the Labrador Trough continue beyond the northern and southern limits of the negative anomaly,

(c) to the north and to the south the western boundary of the Labrador Trough lies approximately along the axis of the anomaly and, since the rocks of the Labrador Trough dip eastward at a shallow angle, it is obvious they do not provide major control of the gravity data.

These arguments do not exclude the sediments of the Labrador Trough contributing slightly to the anomaly.

Another possible source of the negative anomaly could be granites, but as in the Cape Smith Belt there is no surficial evidence for the widespread occurrence of granites and the rather smooth character of the anomaly is not typical of that normally observed over belts of intrusive granitic rocks.

These considerations make it necessary to seek a deep crustal origin for the anomaly.

The presence of a negative anomaly with gentle horizontal gradients flanking a gravity high with much steeper gradients is similar to the pattern observed over one edge of the idealized compensated structure shown in Fig. 5-2. Explanation of the observed anomaly on this basis requires the presence of high density material within the crust and low density material at greater depth. The horizontal gradients of the western limb of the negative anomaly are such that its source could be placed at the base of the crust. This is reasonable as it has already been pointed out that there is no evidence from surface geology for a sufficient quantity of low density material within the upper part of the crust that can account for the anomaly. Although the source of the positive anomaly to the east is a matter of some speculation, the horizontal gravity gradients of the anomaly require that the upper surface of the anomalous mass be no deeper than 15-20 km. It follows that the high grade metamorphic rocks and the basic intrusions to the east of the Labrador Trough may be the cause of the positive anomaly.

The Structural Model: As the presence of basic material within the upper crust to the east of the Labrador Trough can only be assumed from the sketchy geological information, the structural model shown in Fig. 5-8 has been computed on the assumption of a two layered model. The computations have been carried out with the added assumption that the compensated crustal structure is 250 km wide.

Basic rocks or granulites in the upper crust would probably be between 0.1 and 0.3 g/cm^3 denser than normal upper crustal rocks. However, for a density contrast of 0.1 g/cm^3 the anomalous mass must extend to the base of the crust; furthermore, the computed anomaly does not fit the gradients of the observed anomaly as well as do anomalies computed for higher density contrasts. Therefore, a density contrast of 0.2 g/cm^3 has been assumed for the computations.

The agreement between the calculated and observed anomalies is very good for the model consisting of a dense upper layer 15 km thick compensated by a 7.5 km increase in crustal thickness. The near surface mass is shown to have an inward sloping face, but the same gravity effect could be produced by a block model with a gradually increasing density towards the east.

Granulites in the Superior Province: At the western end of the profile part of a local anomaly over an occurrence of granulite is shown. The position of the eastern contact of the granulites with respect to the anomaly suggests that this contact dips outward.

In the interpretation the granulites are shown as part of a "granulite layer", but this is not essential to the interpretation as the same gravity effect could be produced by regarding the granulites as part of a local structure within the Superior province.

5-3-4. Summary of Labrador Trough Interpretation.

The interpretation of the Labrador Trough anomaly has been made on the assumption that the load of high density rocks within the crust east of the Trough is compensated at the base of the crust. On the basis that the granulites and basic rocks within the upper part of the crust have a uniform density contrast of 0.2 g/cm^3, then an upper layer 15 km thick compensated by a layer at the base of the crust 7.5 km thick is required to explain the observed anomaly.

The existence of dense rocks within the upper crust to the east of the Labrador Trough is required by the horizontal gravity gradients which indicate that the source of the anomaly lies within the upper 20 km of the crust. The arguments for the presence of this material at the surface in the eastern complex are based on limited geological information. Alternatives to this interpretation must involve dense material within the crust in the east and probably low density material at depth in the crust or upper mantle beneath the Labrador Trough.

5-4. The Grenville Front

5-4-1. Introduction.

The Grenville Front is perhaps the most fascinating of all boundaries in northern Quebec because, unlike the others, it marks the contact of the Grenville province with two and perhaps three other geological provinces, namely the Superior, the Churchill and the Nain (?). This latter province has been proposed by Stockwell (1965) but more work probably is needed before it is verified as a separate geological province.

Gravity work dates back to 1954 and has continued intermittently thereafter until 1965. The major operation in the area was the regional survey carried out in 1964 by the Observatory. In addition, Grant (1968) has carried out two detailed traverses across the Grenville Front. The work of Innes and Grant will be summarized and discussed as part of the interpretation.

The gravity data available in the far northeastern portion of the Grenville are rather sparse. This area is also one for which regional geological mapping is still underway and this with the lack of gravity data forces this interpretation to be restricted largely to the region between longitudes 65°W and 75°W, which is the same region that was studied by Innes (1957) and Grant (1968).

5-4-2. General Geology of the Grenville.

The surficial distribution of main rock types within the eastern Grenville province is shown in Fig. 5-9. This region of the Grenville has been described previously as a complexly structured region of medium to highly metamorphosed gneisses and schists, intruded on a large scale by anorthosites, gabbros and other intrusive rocks, which last underwent an orogeny about 950 my ago. This description provides an adequate basis for discussion of those features which are believed most relevant to the gravity interpretation.

Metamorphism of the amphibolite and granulite facies exists throughout much of the Grenville. The granulites are of higher grade than those of the Superior province to the north; one notable difference is the more widespread occurrence of garnets in the granulites. Very high grade metamorphic rocks also occur locally around some of the large intrusions. The Grenville gneisses are highly variable which makes it almost impossible to obtain a representative selection for the purpose of density measurements. The average density of these metamorphosed gneissic rocks is estimated to be in the range 2.75-2.80 g/cm^3. This figure is of unknown reliability because of possible different interpretations of inclusions and exclusions, because of lack of knowledge of the relative proportions of each unit and because of the relatively few rocks samples collected.

Another distinctive feature of the Grenville is the absence of volcanic rocks despite the presence of large amounts of intrusive rocks. Volcanic rocks do occur adjacent to the Grenville Front and it is possible that similar rocks occurred throughout the Grenville, but that subsequent metamorphism has altered these rocks sufficiently to be unrecognizable as equivalents of the volcanic and sedimentary sequences to the north of the boundary. The extension of the rocks of the Labrador Trough into the Grenville can be recognized only because of the stability of the iron formation at all grades of metamorphism.

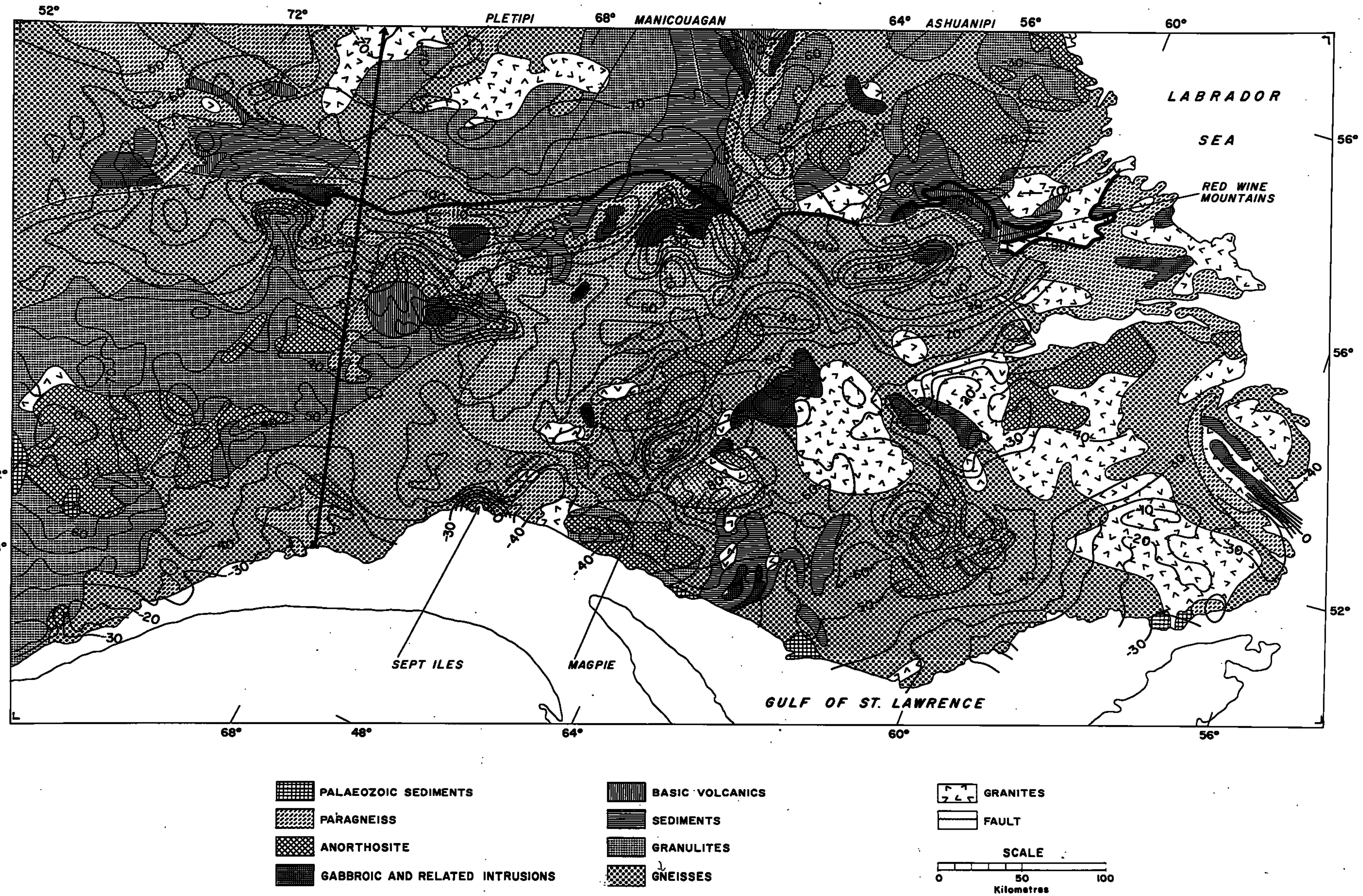
Within the Grenville, east of about 75°W, intrusive rocks of many kinds occur, but the most common types are anorthosites, anorthositic gabbros and granitic rocks. The anorthosites and the related anorthositic gabbros occur throughout the entire region and the individual areas of outcrop range in size from very small to regions of some 15,000 km^2. Granites are not common west of about 64°W, but large areas of these rocks are present east of this longitude. On the basis of earlier discussions this could be interpreted as indicative of a higher level crust to the east. These rocks should not be thought of as textbook occurrences of intrusive rocks because they are intermixed on a large and small scale with country rock and are banded in places. Identification of the rocks is therefore difficult. This complicates the problem of determining reliably the densities of these rocks and only an approximate estimate can be given. The anorthosites probably have a density of about 2.7 g/cm^3 and the anorthositic gabbros are estimated to have a mean density in the range 3.0 to 3.1 g/cm^3.

<u>The Grenville Front:</u> This is usually interpreted as a fault or a zone of distinct change in grade of metamorphism. In the Labrador Trough region geologists usually define it at the biotite isograd. In the far east the situation is much more complex and the position of the boundary may be changed by future work.

Fig. 5-9

The geology and gravity of the eastern part of the Grenville province. Geology after Douglas (1969). Gravity units are milligals.

GENERALIZED GEOLOGY OF EASTERN GRENVILLE



The complexity of the Grenville province has frustrated the efforts of geologists to synthesise the tectonic history of the province. A suggested history since the Proterozoic is as follows:

(a) deposition of the Labrador Trough sequence in the northern Grenville and possibly elsewhere; this sequence of rocks probably extended as far west as longitude 72°W and may even have extended along most of the length of the Grenville Front,

(b) folding during the Churchill orogeny (?),

(c) intrusion, perhaps accompanied by orogeny, of the anorthosites and other intrusion between 1,000 and 1400 my ago,

(d) folding and metamorphism during the Grenville orogeny about 950 my ago,

(e) marine transgression and deposition of sediments during the early Palaeozoic.

5-4-3. Interpretation of the Grenville Front Anomaly.

The Bouguer anomaly field is shown as an overlay to the generalized surface geology in Fig. 5-9. The names shown on the overlay refer to local anomalies that will be interpreted in Chapter 6.

The Grenville gravity low extends eastward from about 73°W. Between this point and the Labrador Trough it follows roughly a straight line which trends slightly north of east. East of the Labrador Trough the situation is less clear, partly because of the lack of data and partly because the geology and structure appear to be more complex. Regional geological mapping is still underway in this region and this with the lack of sufficient gravity data restricts this interpretation to the region west of the Labrador Trough. However, the existing gravity data seem ambiguous with regard to the location of the Grenville Front east of the Labrador Trough. West of the Labrador Trough the Grenville Front lies to the north of the local positive anomalies over the anorthositic intrusions. On this basis the Grenville Front east of the Labrador Trough should be located north of the Red Wine intrusion as shown on existing geological maps. On the other hand the gravity gradient which marks the southern limb of the Grenville low corresponds to the Grenville Front west of the Labrador Trough. If this applies to the east, the Grenville Front should be shown to the south of the position indicated on the map, which would mean that the Red Wine Massif sits astride the Grenville Front. Future gravity work to the east of the Red Wine Mountains may help to resolve this ambiguity, but the definition of the Grenville Front must rest basically with geological studies.

Although the low gravity values along the Grenville Front terminate at about 73°W, the influence of the Grenville Front on the Bouguer anomaly field can be seen well to the west of this longitude. The regional Bouguer anomaly map (in pocket) clearly shows several trends within the Superior province that terminate abruptly at the Grenville Front. One example is the eastward extension of the anomalies associated with the rocks forming what is known as the Timmins-Kirkland Lake mining belt, which is a belt of mainly granitic intrusions and altered basic and acidic extrusive rocks. This rather irregular, east-west trending zone of anomalies terminates abruptly in the vicinity of 74°W which confirms the existence of a major structural discontinuity at the Grenville Front.

The Grenville gravity low is shown in profile in Fig. 5-10 in relation to the surface geology and the topography. At the northern end of the profile over the Superior province the level of the Bouguer anomaly field is about -65 mgal. This level of anomaly is maintained for a distance of some 125 km southward where the level of anomaly gradually decreases to the minimum observed value of about -100 mgal just to the south of the Grenville Front. The Bouguer anomaly then rises rather sharply to a maximum value of about -30 mgal over the Grenville province.

In detail there are local correlations between gravity and geology along the profile in Fig. 5-10. Within the Superior province the Bouguer anomaly field is locally low over the granitic rocks and locally high over the granulites. There also appears to be a very small amplitude gravity low over the sediments of the Otish Mountains just to the north of the Grenville Front. To the south, within the Grenville province, the Bouguer anomaly field is locally high over anorthositic rocks. These local anomalies are not interpreted in this study.

Previously (Chapter 4) it was pointed out that the regional Bouguer anomaly field in the vicinity of the Grenville Front is probably partly related to isostatic compensation for topography. It is necessary to consider the possible effect of the profile of compensation for topography prior to interpreting the profile in terms of crustal structure.

A complete analysis of the relationship of gravity and topography is not possible here, but an estimate of the effect of possible compensating masses can be made on the assumption that compensation takes place at the base of the crust.

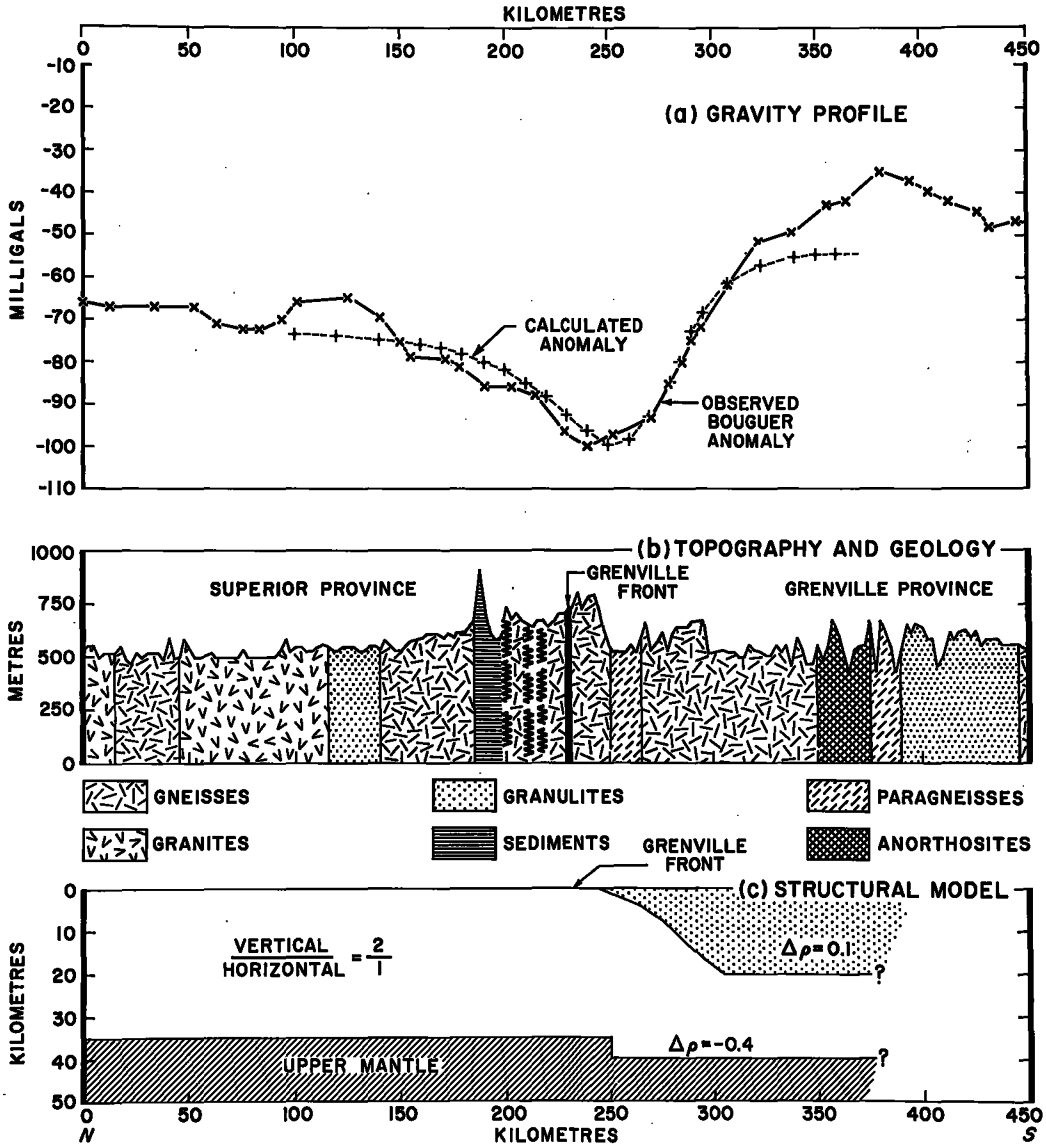


Fig. 5-10

Interpretation of the Grenville low. Geology after Douglas (1969). Topography scaled from maps at a scale of 1:250,000.

The topographic profile shown in Fig. 5-10, which has been taken from topographic maps at a scale of 1:250,000,is probably not typical of the region generally because of the presence of Otish Mountains just north of the Grenville Front. These hills are local to the region of the profile and their presence results in unusually local relief. If the areas to the east and west of the profiles are included in the analysis then the following trends emerge (see also Fig. 4-3):

(a) a gradual rise of 100-500 m between the northern limit of the profile and the Grenville Front,

(b) a more variable topography within the Grenville province (as the profile indicates) which on the average decreases to a mean level about 100-150 m lower than that near the Grenville Front within a distance of approximately 100 km.

If the compensation for topography is assumed to be distributed smoothly at the base of the crust then its effect, reckoned with respect to the apex at the Grenville Front, would be to increase the level of anomaly by 3-5 mgal at the northern end of the profile and by about 6-9 mgal at the southern end of the profile. The effect of compensation for topography can thus at most account for about 10 mgal of the total change in anomaly across the Grenville Front which means that most of the observed change in anomaly must be explained by lateral density variations within the crust.

Cause of the Anomaly: The two previous interpretations of the Grenville low by Innes (1957) and Grant (1968) involve mass distributions within the crust. Both reasoned that the horizontal gravity gradients were too steep along the southern flank of the anomaly to permit a structure to be placed at the base of the crust. Innes suggests that massive granites are the source of the anomaly and Grant attributes the anomaly to the presence of low density, perhaps unmetamorphosed, sediments. The main argument against both hypotheses is the lack of geological evidence for the presence of either type of rock on a sufficiently large scale. It is also difficult to accept the suggestion of low density sediments because of the high degree of metamorphism within the Grenville and because sediments elsewhere within northern Quebec are not the cause of any significant gravity anomalies. Granites and syenites occur locally, but these occur as marginal phases of the large intrusions of anorthositic gabbro which crop out just south of the Grenville Front. It is possible that granitic intrusions cause local gravity anomalies, but they are probably not the principal cause of the Grenville Low. Support for this argument comes from the character of the anomaly itself, which is much more regular than is usually observed over belts of granitic intrusions.

The gravity profile (Fig. 5-10) shows the Grenville low to be similar in character to that observed over the Labrador Trough, which suggests the possibility of a compensated structure. From earlier discussions concerning the relationship of the topography and gravity and the preliminary seismic results of the Observatory, interpretation as a compensated structure is an over simplification. However, such a structure serves as a useful starting point which can be extended to discussion of other possible causes of anomaly.

The Structural Model: The gentle horizontal gravity gradients of the northern limb and the steeper gradients of the southern limb of the Grenville low coupled with higher gravity values over the Grenville province suggest interpretation as a compensated structure. This would consist of an upper high density crust in the Grenville compensated by crustal thickening. The horizontal gradients of the southern limb of the profile restrict the possible depth of the upper mass to 20 km or less. The highly metamorphosed rocks and the anorthositic gabbros which occur throughout the Grenville provide adequate grounds for assuming a higher than normal near-surface density. Large and small outcrops of the intrusive rocks occur throughout the Grenville and these could be regarded as surface expressions of an extensive layer of these rocks. On the other hand, there may be simply numerous pods of these rocks spread vertically and horizontally throughout the Grenville. The correlation of high gravity values with highly metamorphosed rocks has been described earlier and these rocks could undoubtedly be correlated to the high gravity values. Therefore, the density contrast of the upper crustal rocks of the Grenville province is between 0.3 g/cm^3 (for basic rocks) and 0.1 g/cm^3 (for granulites). The problem of the interpretation is thus similar to that for the Labrador Trough. The interpretation will be simplified by assuming a dense upper layer of uniform density contrast that is 250 km wide.

The computed model is shown at the bottom of Fig. 5-10. It appears to be slightly overcompensated in the vicinity of the Grenville Front. This is not serious because the profile is located between two large intrusions which might have influenced structural developments along the profile. The agreement between the observed and calculated profiles could be improved. However, it is difficult to know how best to proceed because there are a number of possible additional causes of the anomaly. Some are:

(a) compensation for topography,

(b) lateral variation of density in the upper mantle as suggested by varying P_n velocities,

(c) granulites which outcrop in the Superior province north of the Grenville Front,

(d) the expected gradual increase in gravity away from Hudson Bay as a result of postglacial inequilibrium.

None of these hypotheses apart from (c) could completely explain the observed changes of gravity because they involve sources that are too deep to explain the gradients of the southern limb of the Grenville low.

Previous discussion pointed out that the maximum effect due to compensation for topography is about 10 mgal. Since this effect would increase the level of the computed anomaly with respect to the axis of the gravity low at either end of the profile and would decrease the width of the anomaly slightly, its inclusion in the interpretation would improve the agreement between observed and calculated profiles.

Not much can be said about the idea of higher densities in the upper mantle because the seismic study has not been completed. However, it would seem that a high velocity layer must be at least 5 km thick to be detected. If it is assumed that the higher P_n velocities imply a density increase of 0.07 g/cm^3 within the upper mantle, then a layer of 5 km thick on either side of the area of the Grenville Front would produce a maximum possible anomaly of about 15 mgal. This would require that the thickness of the compensated structure be reduced.

A proper assessment of the effect of increasing gravity with increased distance from Hudson Bay requires a study of a much larger area than northern Quebec. Innes and Argun-Weston (1965) show an average change of about 10 mgal/thousand kilometres away from the centre of Hudson Bay. On this basis the expected increase from north to south along the profile would only be a few milligals. A correction for this trend would improve the agreement between observed and calculated profiles south of the Grenville Front.

To conclude, the hypothesis of a dense and thicker crust within the Grenville province explains reasonably the observed gravity anomaly. A number of other factors might improve the fit between observed and calculated profiles.

5-4-4. Summary of the Grenville Interpretation.

Like the anomalies over the other structural boundaries the Grenville anomaly can be interpreted as a compensated structure consisting of a dense layer within the upper crust underlain by a thicker crust. The structural model has been calculated assuming that the upper crust in the Grenville province is 0.1 g/cm^3 denser than the upper crust to the north. This is the assumed density contrast for granulite. However, the widespread occurrence of anorthositic gabbros throughout the Grenville province may give rise to an even higher density contrast.

The compensated structure explains only the gross character of the observed anomaly. There are other possible effects which could account for the differences between observed and calculated anomalies.

The seismic data should greatly assist with the interpretation of the gravity data when the analysis and interpretation of the seismic records are completed. The preliminary results (Chapter 4) indicate that there are high velocity zones within the upper mantle and that the crustal thickness is somewhat variable. Except for the Grenville low there are no major regional variations in the Bouguer anomaly field which could indicate a crust of variable thickness. This could mean that the gravity effect expected from a crust of variable thickness is offset by density variations within the crust.

5-5. Discussion of Interpretation Over Structural Boundaries

The interpretation of anomalies over the three structural boundaries in northern Quebec is made difficult because of the lack of evidence from the surface geology for the presence of low density material at the surface to explain the negative anomalies associated with each of the three structural boundaries. The problem is simplified by assuming structures which are compensated at the base of the crust. The development of such structures appears to be a reasonable postulate from the surface geology of each area, although it must be emphasized again that the evidence is not well documented in the area of the Labrador Trough.

The hypothesis of compensated structures requires the presence of large thicknesses of dense rock within the upper crust. In the Cape Smith area geological studies confirm the presence of a huge thickness of basic lavas. In the areas of the other structural boundaries it must be assumed that the granulites and the basic intrusive rocks are the cause of high gravity, but it is emphasized that the horizontal gravity gradients require the presence of dense material somewhere within the upper 20 km of the crust.

The results of this interpretation can be compared with those of Weber and Goodacre (1966) in the Lake Superior region. The gravity data in this region indicate that the Bouguer anomaly field is regionally high, but the seismic data indicate that the crustal thickness varies between 27 and 55 km. To account for this, Weber and Goodacre have postulated that enormous thicknesses of volcanic rock have developed within the crust and in one profile they postulate that the entire crust is composed of high density rock. When placed in this perspective the interpretation suggested here does not create any great problem with regard to the accumulation of the required high density rock within the crust.

Alternative interpretations to those given here would in effect require that the anomalous masses are loads which must be supported by finite strength in the upper mantle. Innes (1957) and Thompson and Garland (1957) have calculated that uncompensated masses producing anomalies with widths and amplitudes comparable to those observed over the structural boundaries in northern Quebec would produce a maximum stress difference between 40 and 100 bars which must be supported at a depth of approximately 50 km. This depth probably represents the upper mantle. The compensated crustal structures postulated in this interpretation imply that most of the stress differences occur within crust rather than in the upper mantle (Lucas, 1966). The crust is probably capable of supporting stress for long periods without adjustment.

It is emphasized that these interpretations have been made without benefit of crustal seismic studies. Seismic data, like gravity data, have ambiguities, but when the two are taken together with the geological data a much more comprehensive interpretation of crustal structure clearly is possible. The seismic data suggest that the crustal thickness is variable and that there are variations of P_n velocities in the upper mantle beneath the Grenville province. Inasmuch as variations of seismic velocity within the upper mantle indicate density variations as well the hypothesis of compensated structures used here may be too simple. However, the hypothesis could readily be extended to include density variations in the upper mantle. The basic extrusive and intrusive rocks observed at the surface were derived by partial fusion of the upper mantle and since partial fusion would probably reduce the relative amount of the lighter elements present in the mantle, a slight density increase with a corresponding increase in the P_n velocity, assuming density and seismic velocity are directly related, might be expected within the upper mantle.

There is a persistent correlation between the occurrence of granulites and high gravity anomalies throughout all of northern Quebec. The widespread occurrence of granulites raises the problem as to whether there is a granulite "layer" present throughout northern Quebec. The answer to this problem is of interest with respect to the development of granitic intrusions in the crust. Granites often occur at a late stage in a tectonic cycle and, as has been pointed out previously, regional metamorphism is also often a late stage tectonic event. If late stage regional metamorphism leads to widespread development of granulites at depth, then a considerable volume of "granitic" material would be forced upward in the crust because this material is unstable in the granulite facies of metamorphism. This could lead to the development of granitic intrusions within the crust. It is interesting to note in this connection that many gravity interpretations (e.g., Bott, 1967) indicated that granitic intrusions extend to a depth of about 10 km, a depth which most geologists believe to be the level at which granulites begin to form.

CHAPTER 6

INTERPRETATION OF ANOMALIES OVER ANORTHOSITIC INTRUSIONS

6-1. Introduction

In this chapter gravity anomalies over six major intrusions are interpreted. These anomalies (Fig. 5-9) have horizontal dimensions as great as a hundred kilometres and amplitudes of up to 90 mgal. This interpretation does not include all anomalies over the anorthositic intrusions because there is too little known about the geology of some of the individual massifs to warrant a gravity interpretation. Even for these major anomalies the geological data available is often sketchy which limits this interpretation to determining the shape of these intrusions. There are regional anomalies surrounding the local anomalies in almost every case, but it will only be possible to consider these regional anomalies to any extent in two areas because of the lack of adequate geological control over the gravity interpretation. This situation will likely remain for years to come because the great areal extent and the complex geology of these intrusions render any geological investigation of these areas a long process.

These intrusions, which are often collectively referred to as the Morin Series, occur in a broad band extending from the Adirondacks in the northern United States to the coast of Labrador. Most of the major geological studies of these intrusions apply to areas located to the southwest of the region considered here. The gravity anomalies over the anorthositic intrusions to the southwest are mainly negative (Thompson and Garland; 1957; Simmons, 1964). In sharp contrast the gravity anomalies over the anorthositic intrusions in the Grenville province east of 73°W are nearly all positive. It is interesting to note that the changeover from predominantly positive anomalies to predominantly negative anomalies takes place at about the western limit of the gravity low over the Grenville Front.

In this chapter the anorthositic rocks will be divided into anorthosites and anorthositic gabbros. This classification is broadly that followed by the Geological Survey of Canada for regional maps of the Grenville. Even this subdivision, although adequate for this interpretation, is oversimplified. Gradations from pure anorthosite to noritic rocks have been reported in nearly all areas where these rocks have been studied. Associated with the anorthosites and gabbroic rocks are more acid rocks which Philpotts (1966) has termed the mangerite series. Mangerites are charnokitic rocks which are probably syenitic in composition. As such they might be termed quartz pyroxene syenites.

Another distinctive feature of these intrusions is the persistent association of magnetite and ilmenite with them. This is particularly true in the eastern Grenville province where massive concentrations of these minerals are reported. Ilmenite is being mined at Allard Lake about 90 miles east of Sept Iles. There are several ore bodies and the reserves are large. The Magpie intrusion contains an iron ore deposit estimated to be in the billions of tons. This deposit is not being mined, but may be in the near future.

The structure of the intrusions is reported to be sheet-like in some areas (Philpotts, 1966) and domical in others (Gross, 1967). An important aim of this investigation is the determination of the dip of the contacts of the anomalous mass. Previous interpretations of massifs of pure anorthosite north of Montreal (Thompson and Garland, 1957) and in the Adirondacks (Simmons, 1964) indicate that these particular intrusions are sheet-like.

As in Chapter 5 it is necessary to assume average densities for the main rock types. The models given in the interpretation have, with one exception, been computed using the following density contrasts in relation to the normal rocks of the upper crust:

(a) anorthositic gabbros: $\Delta\rho = 0.3$ g/cm^3,

(b) anorthosites: $\Delta\rho = 0.0$ g/cm^3,

(c) mangerites: $\Delta\rho = -0.1$ g/cm^3.
(including syenites and granites)

In Chapter 5 the interpretation of the Grenville low required the density of the near surface rocks in the Grenville province to be 2.8 g/cm^3. This conflicts with the above assumption for anorthosites because it is unlikely that the density of pure anorthosite could exceed 2.75 g/cm^3. This is not particularly serious because the intepretation primarily involves the basic rocks. Furthermore, there is little suggestion in Fig. 5-9 of consistently negative anomalies over occurrences of anorthosite. This could mean that the anorthosites occur as thin sheets or that the presence of basic constituents such as olivene has raised the density sufficiently to eliminate the density contrast expected for pure anorthosite.

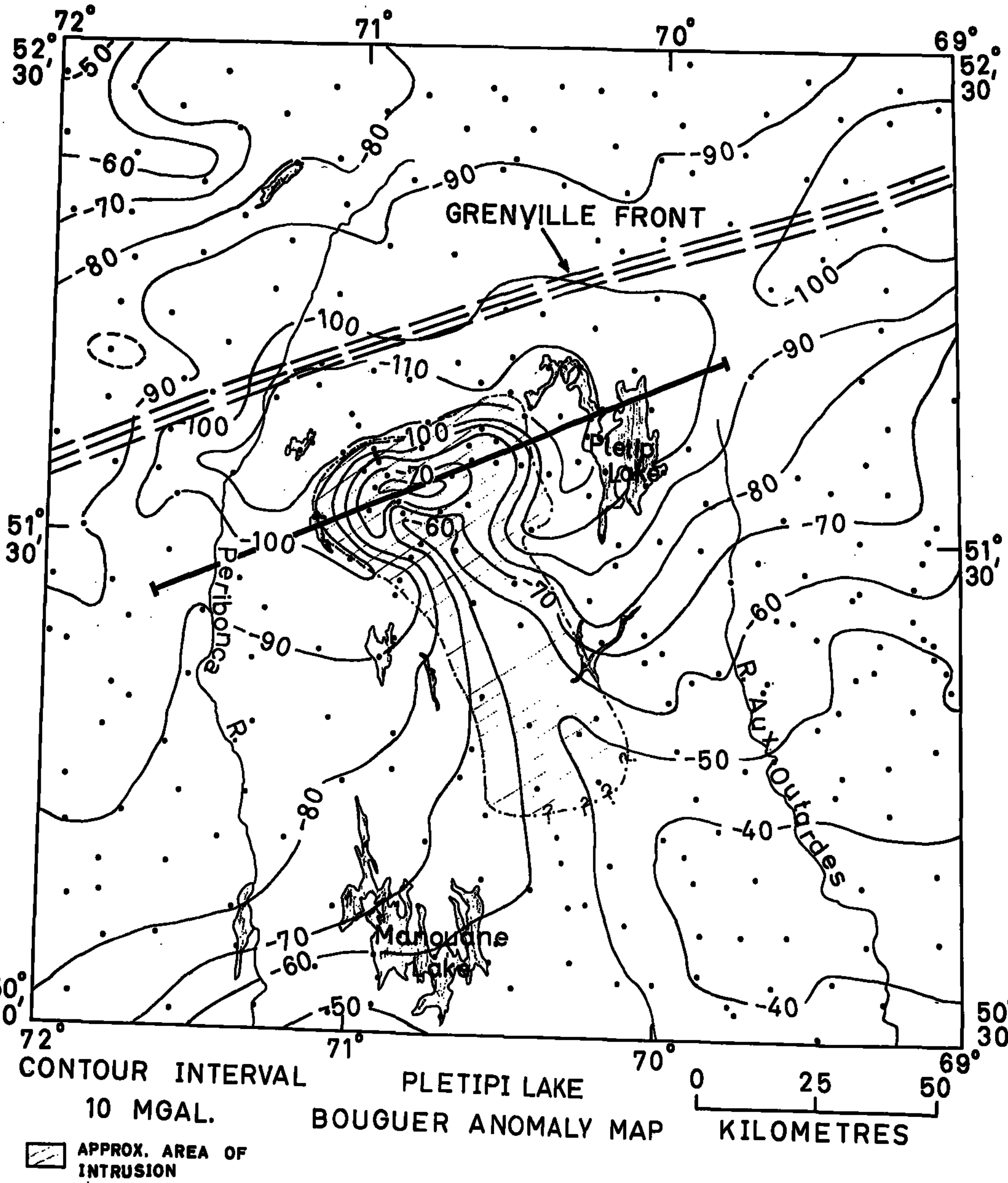


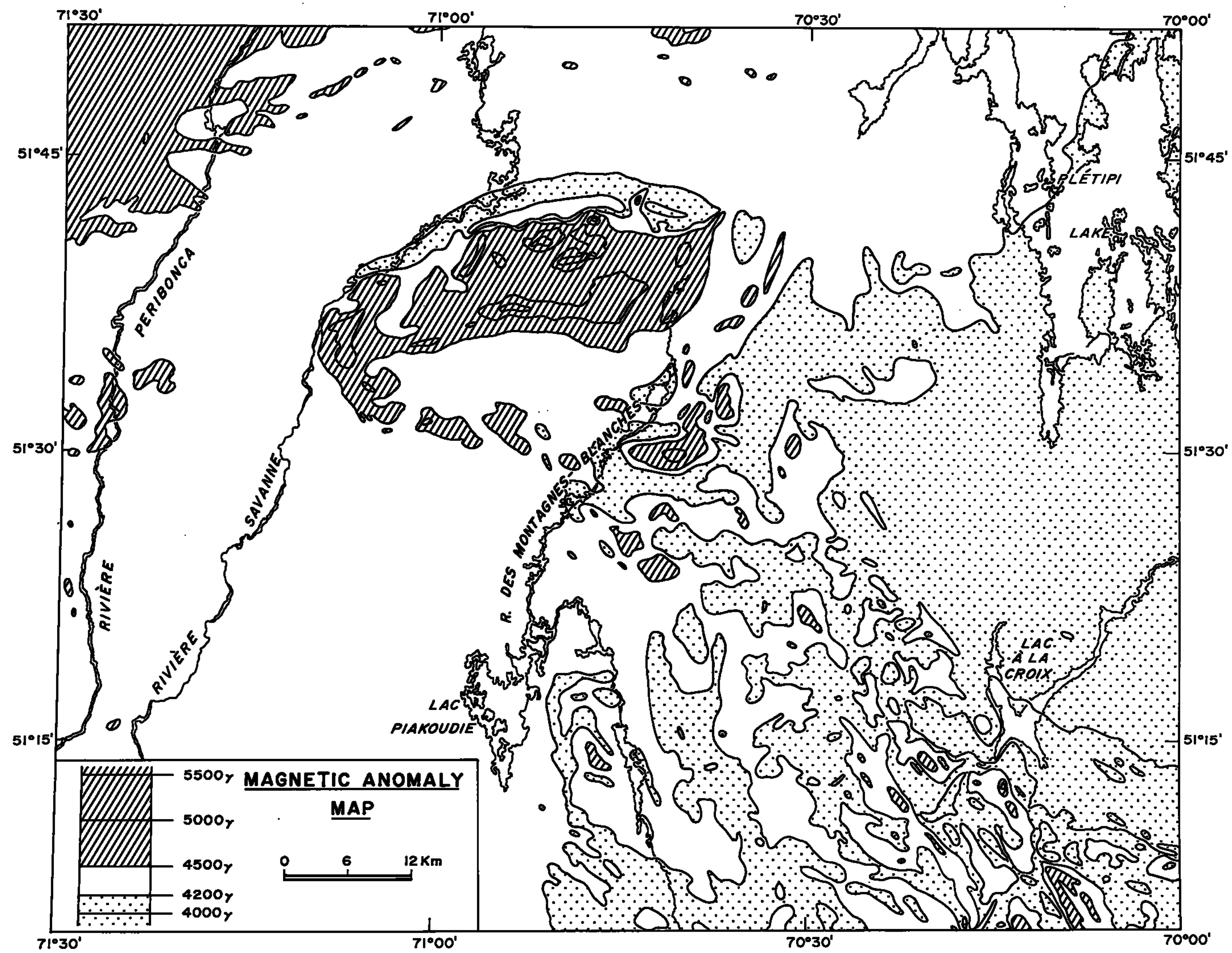
Fig. 6-1
Gravity map of the Pletipi Lake area. The boundary of the basic intrusion is approximate only and is based on field notes, air photos and topographic maps. Gravity units are milligals.

The models shown in the diagrams were first computed by the matrix method described in Chapter 3. The output of the matrix method was then used to compile a polygonal model on the assumption that the structure is two dimensional. This assumption has been tested using the matrix method by applying end corrections. The error introduced by the assumption of two dimensional structures is negligible. Each anomaly was also tested to determine the possible lower limit of the density contrast. With one exception all anomalies could be satisfied by a density contrast as low as $0.2\ g/cm^3$.

6-2. The Pletipi Intrusion

The main anomaly is shown in Fig. 6-1, but the regional map (Fig. 5-9) indicates that this anomaly is only part of a large area of high gravity anomalies extending to the south of the main anomaly. Detailed geological mapping of the intrusion has not been completed, but the regional geological map (Fig. 5-9) shows that the main anomaly is underlain by anorthosite and granulites. The granulites extend southward from the area of the main anomaly along a narrow neck and then broaden out to cover a large area which encompasses outcrops of other anorthosite masses. The association between high grade metamorphic rocks and anorthositic intrusions was pointed out in Chapter 4 and the relationship of the granulites and intrusive rocks shown in Fig. 5-9 suggests that the entire area of granulites may be underlain by intrusive rock. The relatively high Bouguer anomalies to the south of the main anomaly provide partial confirmation of this.

Fig. 6-2 Total field magnetic anomaly map of the Pletipi Lake area.



In this study only the main anomaly is interpreted.

The magnetic anomaly map for the area is shown in Fig. 6-2. The areas of the gravity and magnetic anomalies are virtually identical and both strongly suggest that the intrusive rocks extend southward along a narrow neck leading from the main anomaly to the broad area of granulites to the south. Although the area of maximum gravity anomaly is shown in Fig. 5-9 to be underlain by anorthosites and granulites, the rock types within the region are quite variable. The rock sampling carried out at the Observatory suggests that anorthosite occurs around the northern rim of the intrusion and that a band of anorthosite cuts across the region from northeast to southwest. Confirmation of this comes from the magnetic data which show this northeast-southwest zone to be rather featureless. Elsewhere within the region of maximum gravity anomaly the rocks are more variable with both anorthosites and basic rocks present. There is one small area in which a rock consisting entirely of magnetite and olivine was found.

An east-west profile across the Pletipi anomaly, chosen to avoid complications due to the anomaly over the neck and the main Grenville anomaly, is shown in Fig. 6-3. The profile shows a sharp positive anomaly over the intrusion flanked by negative anomalies with much gentler horizontal gradients on either side of the intrusion. In addition, there is a local negative anomaly on the eastern limb of the positive anomaly. The total width of the positive anomaly is about 60 km and its amplitude can be placed at between 50 and 80 mgal depending upon the regional anomaly assumed. The general shape of the profile is

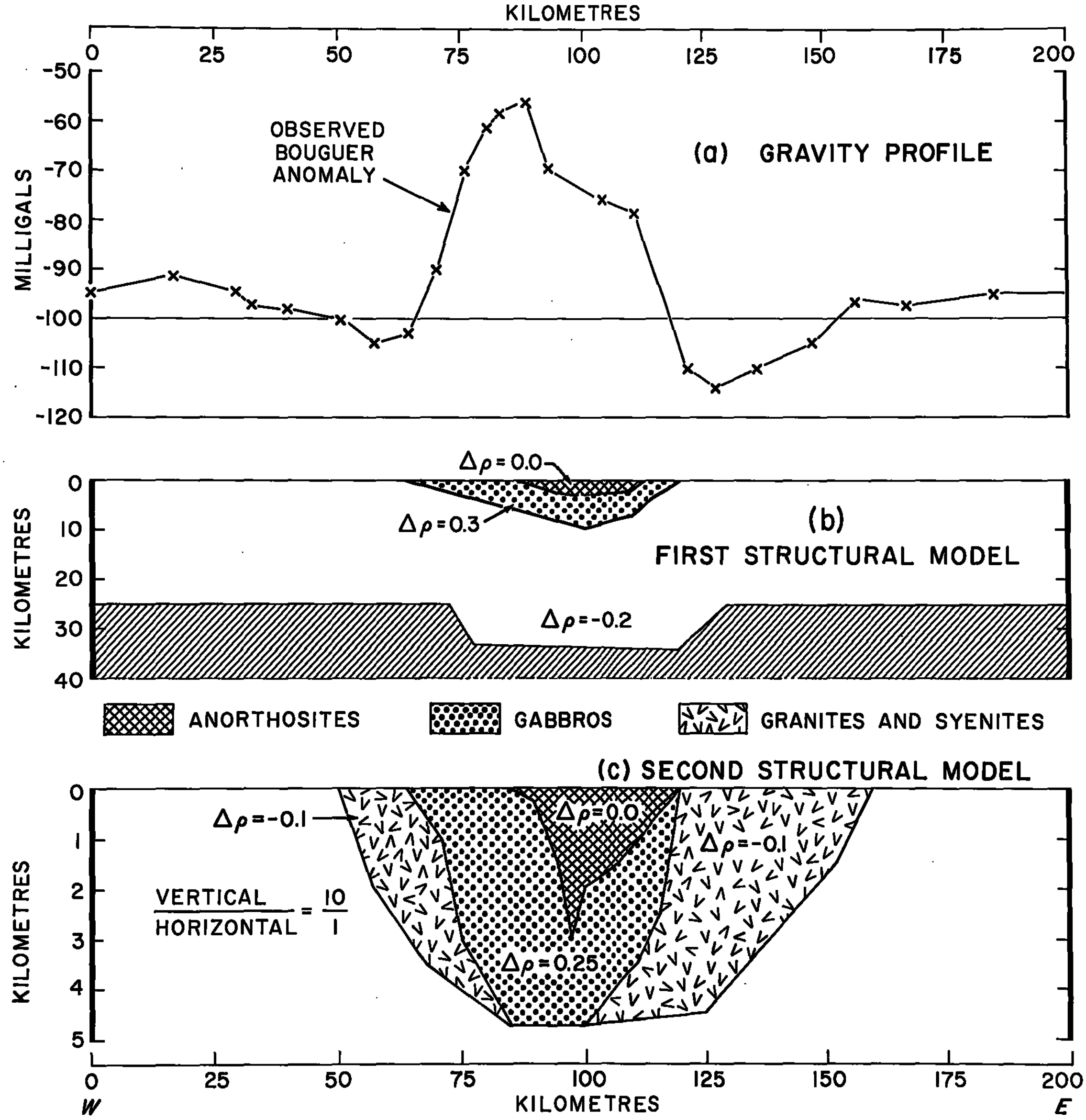


Fig. 6-3

Interpretation of the Pletipi gravity anomaly. Note the large magnification of the vertical scale of the lower model. The calculated anomalies from both models fit the observed anomaly to within 2-3 mgal.

similar to that expected over a compensated structure.

The positive anomaly over the intrusion clearly indicates that basic rocks dominate within the intrusion. The local negative anomaly on the eastern limb of the intrusion overlays the northeast trending zone of anorthosites. The source of the negative anomalies flanking the positive anomaly is a problem. Mangeritic rocks do frequently occur around the margins of these intrusions either as marginal phases or separate local intrusions (Gross, 1967). Since the negative anomalies are part of one continuous fairly smooth anomaly around the perimeter of the positive anomaly, it would appear that the granites and syenites, if present, are themselves continuous and are therefore more likely a marginal phase of the basic intrusion. The alternative to granites and syenites as the cause of the negative anomaly is warping within the crust along some density discontinuity.

Models constructed on the basis that the low gravity values adjacent to the intrusion are caused respectively by granites and syenites and by warping along some layer within the crust are shown in Fig. 6-3. The anomaly calculated from each model agrees with the observed profile to within 2-3 mgal.

If the flanking negative anomaly is caused by granites and syenites then a marginal phase larger than the basic intrusion is required. A density contrast greater than assumed in the diagram would reduce the thickness of granitic rocks but would not reduce the width over which these rocks outcrop. The presence of a large marginal phase of mangeritic rocks has been reported by Philpotts (1966) in the Morin area. In the Morin area the mangeritic rocks are more extensive at the surface than the anorthositic rocks.

The alternative to mangeritic rocks as the cause of the surrounding gravity lows is to assume downwarping of the underlying crust. This interpretation is interesting because, unlike the interpretations over the structural boundaries, the compensating mass cannot be placed at the base of the crust. The model shown in the diagram involves a block structure at a depth of 20 km, which is the maximum depth at which such a structure can be placed. The density discontinuity would have to be interpreted as the top of an intermediate layer and the difficulty with this interpretation is the lack of evidence from seisimic studies for an intermediate layer in the eastern part of the Canadian Shield. The recent seismic experiment in the Grenville province may resolve the question of the existence of an intermediate layer in this area.

On the basis of the available evidence it is suggested that the regionally low gravity values surrounding the Pletipi gravity high are most likely caused by a low density marginal phase of the intrusion.

In Fig. 6-3 the contacts of the basic intrusion dip inwards. This conclusion seems inescapable for the following reasons:

(a) the magnetic field is featureless beyond the edges of the anomaly and therefore the limits of the magnetic anomaly probably define the limits of the intrusive rock,

(b) the area of the gravity anomaly is nearly the same as that of the magnetic anomaly,

(c) the regional geological maps and the air photos suggest that the contacts of the intrusion coincide approximately with the limits of the gravity anomaly,

(d) the steep horizontal gradients near the margins of the gravity anomaly (Fig. 6-3) are not usually observed over anomalous masses with outward sloping contacts.

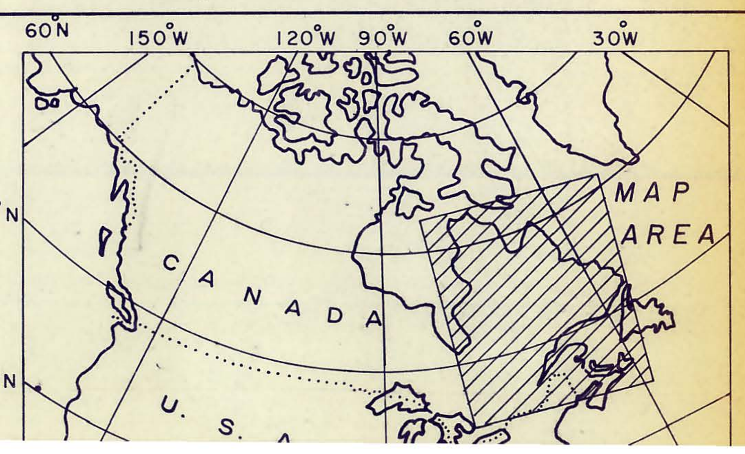
6-3. The Magpie Instrusion.

The Magpie anomaly covers an area which is shown on the geological maps as underlain by gneisses (Fig. 5-9), but the steep gradients of this large positive anomaly indicate that a considerable amount of basic rock is required fairly near the surface. An attempt was made by the writer to obtain more information by carrying out a detailed gravity and rock sampling traverse across the feature. Unfortunately, the aircraft broke down and the work was not completed. The few rock samples collected indicated the presence of anorthosite and a basic rock containing huge crystals of pyroxene. Additional geological information has been provided by Dr. E.R. Rose (Geological Survey of Canada, personal communication) who has studied a small region in the vicinity of the huge magnetite deposit located near the northeastern bounday (at 51°25'N, 64°05'W) of the gravity anomaly. In this small area the country rock consists of gray granitic gneisses which have been complexly folded and faulted. These rocks are intruded by anorthosite and gabbroic anorthosite. Late stage granites have intruded both the gneisses and the

Fig. 6-4

Gravity anomaly map of the Magpie Lake area. The distribution of intrusive rocks is after Gross (1967). The gravity units are milligals.

INDEX MAP



QUEBEC
CANADA

BOUGUER GRAVITY ANOMALIES
contoured at intervals of 10 milligals

SCALE 0 50 100 200 MILES
0 100 200 KILOMETRES

Dominion Observatory,
Ottawa, Canada
March, 1966

Compiled and drawn by N. B. Babey