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A Preliminary Analysis of the Gravity Anomaly Field in the Timmins-Senneterre Mining Areas with map

No. 58-Timmins-Senneterre
Mining Areas

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CANADA

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R. A. Gibb, J. J. G. M. van Boeckel and R. W. Hornal

ABSTRACT - The results of gravity surveys made by the Dominion Observatory, during the period 1946 to 1963, in the Timmins-Senneterre mining area of Ontario and Quebec are presented as a Bouguer anomaly map (scale: 1:500,000). The area is studded with many granite batholiths of variable composition which are outlined by intense negative gravity anomalies. The whole region is regarded as one great roof pendant and on the assumption that the volcanic and sedimentary rocks of the area are everywhere floored by granite, it is possible to estimate the thicknesses of the volcanic belts using the gravity results; however, the depths to which the granite extends cannot be determined by the gravity method alone. A preliminary interpretation using two- and three-dimensional models to simulate major geological bodies indicates that many of the dense volcanic belts in the area extend to depths of from 3 to 5 km.

RÉSUMÉ - Les résultats des études gravimétriques effectuées de 1946 à 1963 par la Direction des observatoires dans les régions minières de Timmins, en Ontario et de Senneterre, au Québec sont présentés sous forme d'une carte d'anomalies de Bouguer à l'échelle de 1:500,000. La région est parsemée de batholithes granitiques à composition variable qui sont délimités par des anomalies de gravité négative intense. Toute la région peut être considérée comme un immense lambeau témoin; en supposant que les roches volcaniques et sédimentaires de la région reposent partout sur du granit, il est possible d'évaluer les épaisseurs des zones volcaniques à l'aide des résultats gravimétriques; cependant, il est impossible de déterminer les profondeurs du granit par la méthode gravimétrique uniquement. Une interprétation préliminaire faite à l'aide de modèles à deux et à trois dimensions, simulant les masses géologiques les plus importantes, indique qu'un bon nombre des zones volcaniques denses de la région atteignent des profondeurs de 3 à 5 kilomètres.

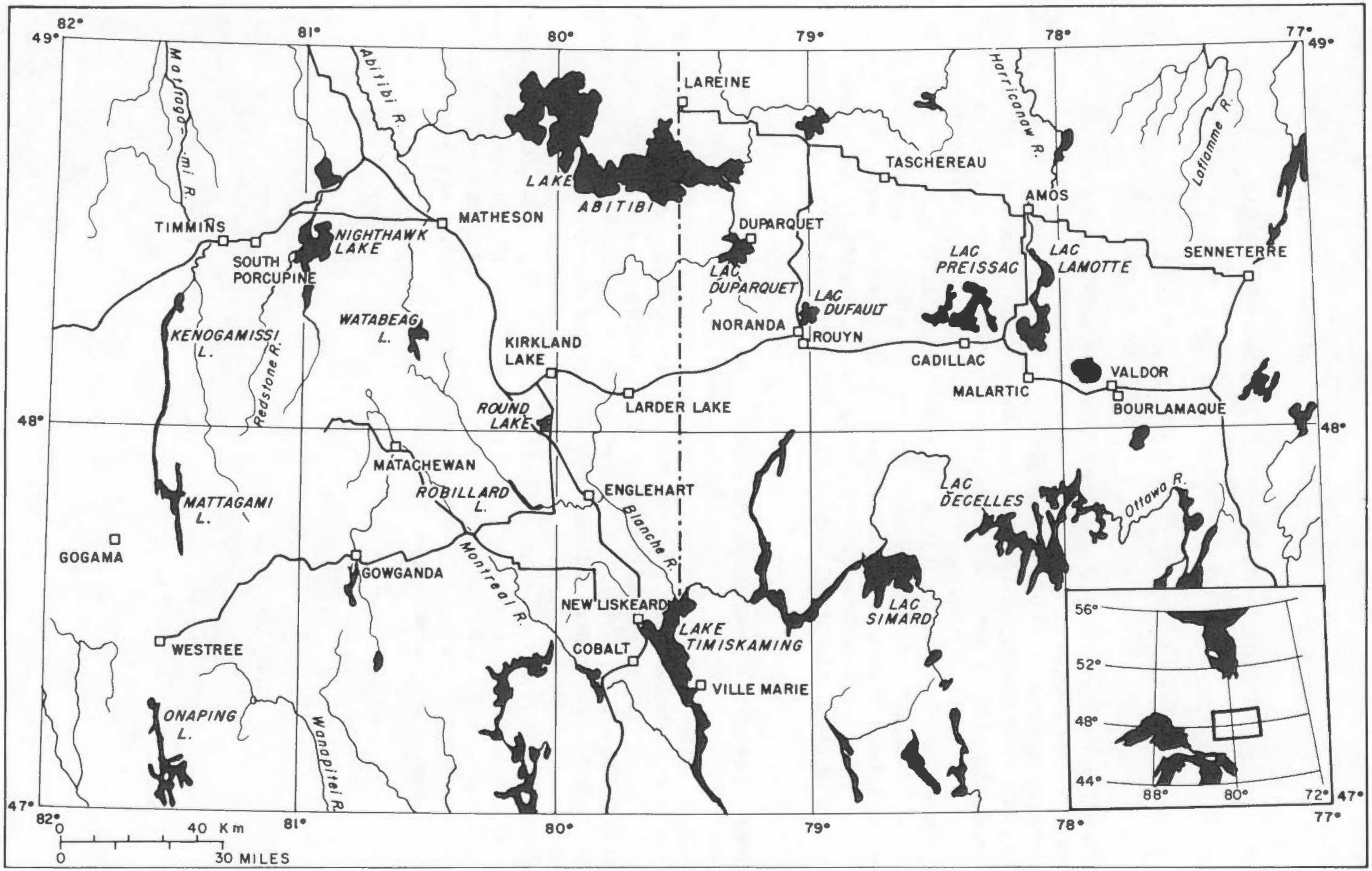

Figure 1. Location map of the Timmins-Senneterre mining area.

INTRODUCTION

In this report possible relations between Bouguer gravity anomalies and Precambrian geology are described for an area of the Canadian Shield defined by latitudes 47°N and 49°N and longitudes 77°W and 82°W (Figure 1). This area, here referred to as the Timmins-Senneterre mining area, or simply the mining belt, has been important for the production of gold, silver and base metals since silver was first discovered in the Cobalt area in 1903. The ores are mainly associated with major easterly trending structural 'breaks' or faults and related cross-faults which traverse many different rocks so that the ores do not appear to be related to any particular type of rock.

Since 1946 Dominion Observatory field parties have made several gravity surveys in this region. The results of these surveys have been compiled in the form of a Bouguer anomaly map (in pocket).

The first discussion of the gravity anomalies in this region was presented by Garland (1950), who separated the anomalies into regional and local components. He related the regional effects to variations in the thickness of the granitic layer of an assumed layered crust and showed that the local anomalies correlate well with the surface geology. He found that the Keewatin greenstones produce marked positive anomalies due to a large density contrast (0.25 g/cm^3) with the granitic rocks. The maximum thickness of the greenstones derived from the gravity results was about 3 km.

GRAVITY OBSERVATIONS

The gravity work done by the Dominion Observatory in the mining belt is summarized in Table I. The early gravity surveys have been described by Garland (1950), Innes and Thompson (1953), Thompson and Garland (1957), and Innes (1960). For this report all the gravity data have been recomputed using more recent elevation information and upgraded gravity base values. An estimate of the mean error in the Bouguer anomaly values is $\pm$ 1.5 mgal.

All the stations, which total 2,200, are not shown on the Bouguer anomaly map because the station intervals vary from a few hundred metres in detailed surveys to twelve kilometres in regional surveys. However, the principal facts of all stations and location sketches of all control stations are filed in the Gravity Division, Dominion Observatory, Ottawa and are available on request.

SUMMARY OF THE GEOLOGY

The rocks of the mining belt are described in numerous reports of the Ontario Department of Mines, the Quebec Department of Mines and the Geological Survey of Canada. Only a summary of the geology of the mining belt is given here, but a geological map of the area (in pocket) has been compiled from various published sources.

Table I

Dominion Observatory Gravity Surveys in the Mining Belt

Year	Observer	Gravimeter	No. of Stations
1946	A. H. Miller	Atlas Mott-Smith	23
1947	A. H. Miller	Atlas Mott-Smith	73
1949	M. J. S. Innes	North American No. 85	49
1951	R. Bedford and A. Larochelle	North American No. 85	510
1956	A. M. Bancroft	North American No. 85	254
1958	B. G. Brulé	Worden 433	58
1963	R. K. McConnell	Wordens 391, 433	590
1963	J. J. G. M. van Boeckel	Worden 433, Canadian 132	610
1964	J. J. G. M. van Boeckel	Worden 573	33

The oldest known rocks in the area are Archaean and consist of basic to acidic lavas with some interbedded sediments. This succession, called Keewatin, may be up to 13 km thick according to geological estimates of stratigraphic thickness. At the end of Keewatin time the accumulation of these Archaean basalts, andesites, tuffs and agglomerates was followed by folding and erosion and the Timiskaming sediments were laid down unconformably on the Keewatin series. The Timiskaming series consists mainly of greywacke and slate with conglomerate near the base (Harrison, 1957). These Timiskaming sediments are of particular importance because they often mark the continuous gold-bearing structures in the mining belt.

At the close of the Archaean both the Keewatin and Timiskaming series were involved in orogeny during which vast Algoman granitic batholiths were emplaced. At the same time the Archaean rocks were invaded by numerous stocks and dykes varying in composition from syenite and granite to gabbro. A long period of erosion was followed by deposition of the Cobalt series (greywacke and quartzite). These rocks were later intruded by dykes and sills of Nipissing diabase.

In the southeastern corner of the mining belt the east-west strike of the formations of the Superior province is cut off by the northeast trending Grenville front, which forms the northern boundary of the Grenville province. An outlier of Palaeozoic rock is preserved in the downfaulted block northwest of Lake Timiskaming as a remnant of a former sedimentary cover.

ROCK DENSITIES

During the 1963 surveys, 347 fresh rock samples were collected for density determinations. The results which are regarded as representative of the main rock types in the mining belt, are given in Table II.

Table II

Rock Densities in the Mining Belt

Rock Type	No. Samples	Density Range (g/cm^3)	Mean Density (g/cm^3)
Precambrian			
Igneous rocks			
Syenite	8	2.62 - 2.75	2.66
Granite	68	2.54 - 2.74	2.65
Granodiorite	29	2.61 - 2.84	2.72
Diorite and quartz diorite	27	2.63 - 2.90	2.75
Gabbro	20	2.83 - 3.06	2.96
Diabase	33	2.78 - 3.06	2.95
Acid volcanics	5	2.64 - 2.72	2.68
Andesite	22	2.69 - 2.95	2.81
Basalt	31	2.86 - 3.18	2.94
Metamorphic rocks			
Granitic gneiss	16	2.62 - 2.71	2.67
Basic gneiss	19	2.70 - 3.11	2.85
Metasediments	27	2.57 - 2.90	2.72
Greenstones	20	2.78 - 3.11	2.94
Sediments			
Greywacke	8	2.66 - 2.84	2.74
Mudstone	10	2.72 - 2.82	2.76
Palaeozoic			
Sediments			
Mudstone	4	2.31 - 2.39	2.36

DESCRIPTION OF THE BOUGUER ANOMALY FIELD

The Bouguer anomaly field in the mining belt has a complex pattern and several factors suggest that it is closely related to the surface geology. Gravity lows of large extent and of great magnitude occur over granite batholiths in contrast to the often more elongated gravity highs which are underlain by dense volcanic rocks. The northern part of the survey area is dominated by easterly gravity trends similar to those of the Cadillac-Larder Lake and Destor-Porcupine fault zones (Wilson, 1948; Dresser and Denis, 1944) and other major structural trends of the area. In the southeast there is an extensive gravity low over the area of the Southern (Pontiac) granite to the north of the Grenville front. In the southwest a zone of relatively positive

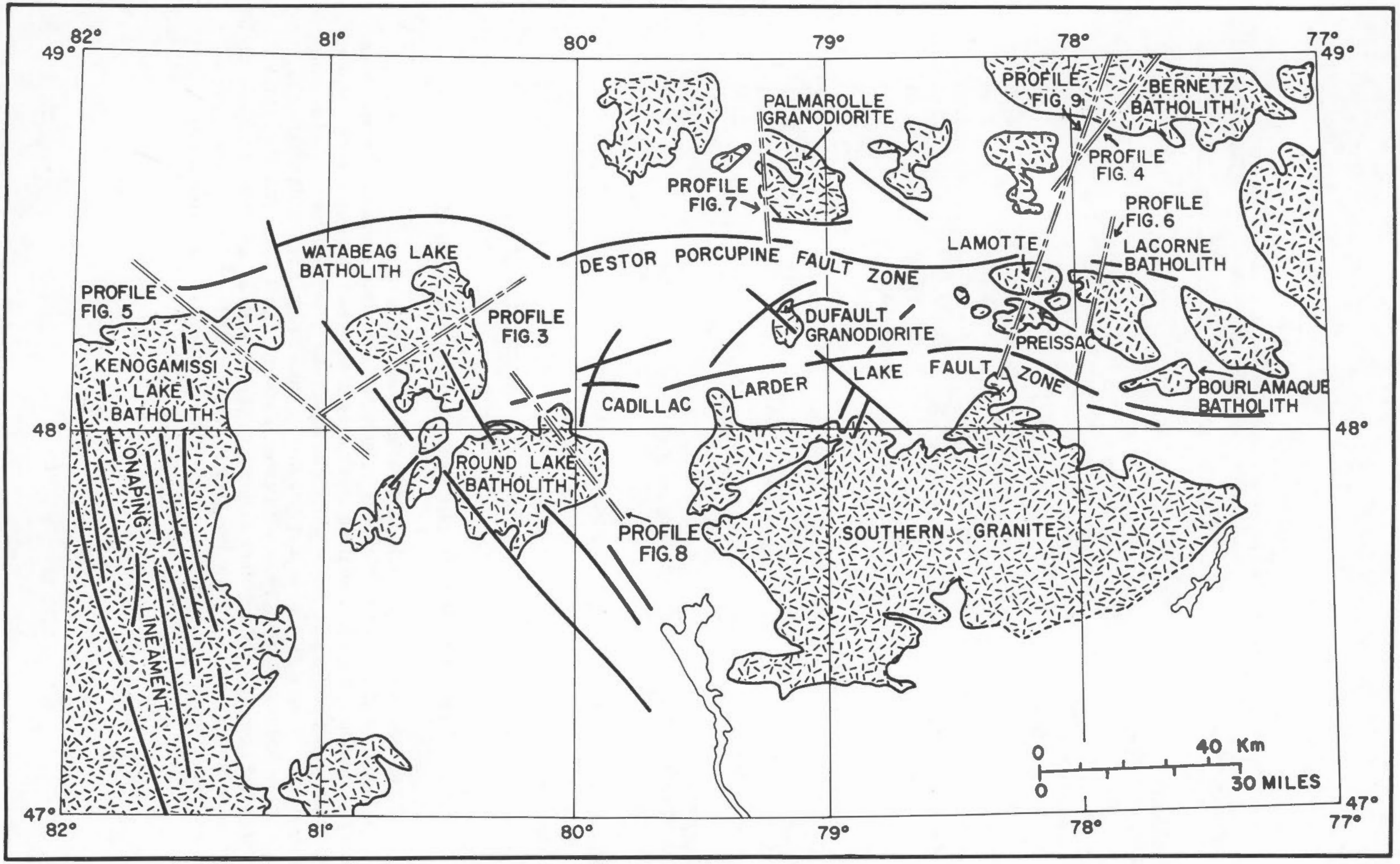

Figure 2. Distribution of granite batholiths and locations of gravity profiles of Figures 3 to 9.

anomalies overlies the southern portion of the Onaping lineament (Wilson, 1948) (see Figure 2). Between these areas is a narrow zone of positive anomalies corresponding in trend to the Lake Timiskaming lineament (Wilson, 1948), where the anomalies are irregular and often bounded by steep gravity gradients.

Mean Anomalies

Mean Bouguer and free-air anomalies and mean elevations for every degree square in the mining belt are presented in Table III.

Table III

Mean Bouguer and Free-air Anomalies and Elevations by Degree Square

	Degree Square		
	Mean Bouguer Anomaly	Mean Free-air Anomaly	Mean Elevation
Timmins	- 45	- 12	963
Matheson	- 42	- 9	987
Abitibi	- 49	- 16	960
Taschereau	- 53	- 20	1007
Senneterre	- 51	- 15	1036
Gogama	- 38	4	1247
Montreal River	- 44	- 15	1014
Lake Timiskaming	- 33	- 6	801
Lac Simard	- 59	- 16	990
Grand Lake Victoria	- 47	- 9	1122

The Bouguer anomalies are all negative. The maximum value of -4 mgal occurs over outcrops of Nipissing diabase near New Liskeard and the minimum value of -82 mgal occurs over the Lacorne batholith about 45 km west of Senneterre. The mean Bouguer anomaly for all stations is -45 mgal.

A measure of the isostatic balance of the area may be obtained approximately because the effect of compensation is about equal and of opposite sign to the attraction of the topography (Innes, 1960). For an infinite slab of rock 1000 feet thick and of density 2.67 g/cm^3 the attraction is 34 mgal. This implies that the area as a whole is over-compensated by 11 mgal, a result which agrees with the mean free-air anomaly of -11 mgal for this region. As might be expected, this result closely agrees with that obtained by Innes (1960) for a much larger segment of the Shield which included the western part of the present area. Innes (1960) and Innes and Argun-Weston (1966) have detected a systematic decrease in the average free-air anomalies from -10 mgal to -15 mgal toward Hudson Bay over the Shield reaching a minimum of -26 mgal in the vicinity of Hudson Bay. They have concluded that these results may reflect incomplete isostatic adjustment following deglaciation although they suggest that this effect may be superimposed upon tectonic effects having a much longer time scale.

INTERPRETATION

The Bouguer anomalies in the Timmins-Senneterre mining belt are largely controlled by the distribution and shapes of granite batholiths, the distribution and thicknesses of volcanic-sedimentary belts, and the densities of these rocks. Gravity lows occur over most of the batholiths, whereas the highest gravity values occur over basic volcanic piles and ultrabasic intrusions. Such correlations are generally found elsewhere in the Canadian Shield (Garland, 1950; Innes, 1960).

It is convenient in this preliminary interpretation to discuss separately the anomalies associated with the granite batholiths and those associated with the volcanic rocks.

Composition and Density of the Granites

In this study 'granite' is used in the wide sense to mean any of the acid igneous rocks of medium to coarse grain size. The granites of the mining belt vary considerably in composition from intrusion to intrusion and often within the same pluton. Granodiorite and quartz diorite are common with lesser amounts of true granite. More basic rocks such as diorite and even gabbro often occur as marginal phases of the plutons. Syenite of variable composition occurs throughout the area but generally in stocks and dykes often too small to be delineated by the regionally spaced gravity stations.

The distribution of the larger bodies of granite was controlled by the regional structure of the area. Many of the intrusions occur near the summits of anticlines in Keewatin rocks which were folded before intrusion (Cooke, James and Mawdsley, 1931). Several phases of intrusion took place; some masses are mutually intrusive, others have more acidic late phases, and some have later basic phases. Gradational contacts often occur and large stoped masses of country rock are found in all degrees of assimilation. Many of the granites are massive, coarse-grained or porphyritic types while others are gneissic. Granite pebbles in Timiskaming conglomerates indicate that in addition to the post-Timiskaming granites, bodies of pre-Timiskaming granite also existed (Cooke, James and Mawdsley, 1931).

A knowledge of the differences in composition found in the granites is important in the interpretation of the gravity anomalies. Each acid rock type has a characteristic range in density although the ranges in density of the different rocks usually overlap considerably, as shown in Table IV. This table has been compiled from the results published by Roddick (1967) and Gibb (1968), and from a Dominion Observatory file.

Table IV

Mean Densities of Some Intrusive Rocks from Canada

Rock type	No. Samples	Density Range (g/cm^3)	Mean (g/cm^3)
Syenite	101	2.50 - 2.92	2.65
Granite	1426	2.55 - 2.70	2.65
	44		2.62
Quartz Monzonite	349	2.55 - 2.76	2.65
Granodiorite	849	2.56 - 2.84	2.68
	1023		2.70
Quartz diorite (tonalite)	1179	2.60 - 2.90	2.75
Diorite	137	2.60 - 2.96	2.75
Gabbro	274	2.74 - 3.24	2.96

As previously mentioned, some granites in the mining belt do not have associated negative Bouguer anomalies. Some bodies are too small to be detected with the station spacing used. Others are not truly granitic in composition. The Bourlamaque batholith is outlined by moderately high anomalies, as is a part of the Palmarolle granodiorite and some parts of the granitic rocks around Westree. These examples illustrate the sensitivity of the gravity meter to changes in the composition of the magma. The Bourlamaque batholith consists mainly of albite tonalite formed by soda metasomatism from what was originally a quartz gabbro (Gussow, 1937). There is therefore no reason to expect a large gravity low here. Similarly a facies change in the Palmarolle granodiorite to a dioritic or gabbroic phase (Cooke, et al., 1931) is the reason for the local high in this area, as will be shown in a later section.

Since the detailed geology and the variations in density of many of the granites are unknown in detail and since the gravity stations are often regionally spaced the present interpretation of the results must be regarded as preliminary. The Preissac-Lacorne batholith is an exception. Dawson (1966) has made a comprehensive study of this pluton. He has measured the density of 272 samples collected from the pluton and country rocks and has derived a shape and thickness for the granite from the gravity anomaly. The Dufault granodiorite has also been mapped in some detail (Cooke, et al., 1931); however, it is one of the smaller bodies which have little effect on the widely spaced gravity stations. The Round Lake batholith has been mapped by Lawton (1954) and a more detailed gravitational study of this pluton will be published separately. Parts of some of the other larger bodies have been mapped in detail; for example the work of Freeman (1957 a and b) and Chagnon (1961) has emphasized the complexity of the Southern (Pontiac) granite which is delineated by the most extensive gravity low in the area. Most of the other bodies have been mapped by reconnaissance methods although additional petrographic information is available for some in reports by Cooke, et al. (1931) and Gussow (1937).

Negative Anomalies over the Granite Batholiths

Within the last two decades it has been widely recognized that negative gravity anomalies occur over granites. Important contributions to this field of study have been made by Bott (1953, 1956 and 1961) who concluded that the upper crust must be denser than granite by about 0.1 g/cm^3, and by Bott and Smithson (1967). Garland (1965) has pointed out that the problem is complicated in shields because of the old practice of mapping large areas of metamorphic rock as granite. He suggests that the average density of the metamorphic rocks exposed in shield areas is probably of the order of 2.76 to 2.78 g/cm^3 so that there is again a density deficiency of about 0.1 g/cm^3 in the case of massive granite.

The problem is further complicated in shields because often in such areas granite virtually becomes the country rock. The term 'granite' is used here to include all granitoid rocks of various origins, compositions and textures. Estimates of the average composition of the surface rocks of the Canadian Shield are granodiorite (Grout, 1938), a composition equivalent to granodiorite, mica gneiss or greywacke (Shaw, et al., 1967) in northern Ontario, and granodiorite in northern Manitoba (Gibb, 1968). This composition implies an average density of 2.67 to 2.70 g/cm^3 for the upper crust in the Shield area, which may be equated to the so-called 'granitic layer'. As noted above this value of 2.67 g/cm^3 is lower by about 0.05 to about 0.15 g/cm^3 than the mean density of the rocks of the Phanerozoic mobile belts which border the Canadian Shield on almost all sides. This difference in density of the upper crustal rocks provides a possible contribution to the consistent regional Bouguer gravity anomaly level of about -45 mgal over the Canadian Shield. A density contrast of -0.1 g/cm^3 and a granitic layer about 10 km thick could explain this anomaly.

It is assumed that in the mining belt the volcanic sedimentary belts are everywhere floored by granite which extends to unknown depths presumably to the base of the granitic layer. This assumption follows Halet (1948) who regarded the whole area as one great roof pendant. The local thicknesses of the volcanic belts can be estimated from the gravity data whereas only a broad estimate of the depth to the floor of the granitic layer could be given without other controls. Thus the depths to the base of granites given in the next section are apparent depths and represent the thickness of adjacent volcanic belts because the exposed granites 'floor' in granite of the granitic layer assumed to be homogeneous for this interpretation.

With the reservation that variations in composition in the batholiths are not known in detail, the information that is available may be used with the gravity results to give preliminary estimates of the apparent depths of the batholiths. In view of the many variables in the data a rapid method of computing the apparent depths and shapes of the batholiths for different density contrasts was required. The first method used was that of Tanner (1967) who has published an automated matrix method of gravity interpretation in which the anomalous mass is assumed to be two-dimensional but three-dimensional structures may be approximated by applying end corrections. In one application of his method Tanner developed a computer program called Granite Bodies based on the assumption that the margins of the anomalous mass slope outwards. This program has been used extensively to study the granitic intrusions of the mining belt. The program may be used not only to determine the shapes of models which can satisfy the observed gravity anomaly but also to estimate practical lower limits for the depth to the upper surface and to estimate the practical range of the density contrasts. The limits for the solution may be recognized from evidence of instability in the solution or systematic differences between the observed and calculated anomalies on the margins of the anomaly. A similar program called Sedimentary Basins (Tanner, 1967) for bodies with inward-sloping margins was also used to study the shape of the sedimentary-volcanic belts. Other models were constructed using the two- and three-dimensional methods of Nagy (1964 and 1966). The distribution of the granites described in the following sections is shown in Figure 2, which also shows the various profile locations.

Watabeag Lake Batholith. A sketch map showing the extent of the Watabeag Lake batholith and its associated gravity anomaly is shown in Figure 3. The gravity stations are also shown in Figure 3. The values at the stations on and around the batholiths were recontoured for all the gravity lows selected for interpretation so that slight differences in contouring may be seen when compared with the Bouguer anomaly map, which was contoured by interpolating linearly between stations. The outline of the granite is based on the Timmins-Kirkland Lake map sheet (Ontario Dept. of Mines, 1964). The granite is largely covered by deposits of sand and gravel (Wright, 1922) apart from the margins; however, the intense Bouguer anomaly (minimum value -65 mgal) centred to the east of Watabeag Lake and a few isolated outcrops permit the confident assumption that the unexposed central region is indeed granite. Wright (1922) mapped the batholith as mainly granite and syenite porphyry. Lovell (1967) has mapped the southwestern part as mainly granite with some quartz diorite occurring chiefly as a border facies.

The Granite Bodies program was used to derive a model of the shape and apparent thickness of the granite. End corrections were applied in this case and in all other applications of this method to the granites which cannot be regarded as two-dimensional structures. In view of the paucity of geological outcrops, the granite was assumed to be homogeneous. Four different density contrasts between the granite and the volcanic rocks were used in the calculations to place some reasonable limits on the apparent thickness. The density contrasts used were 0.15, 0.20, 0.25 and 0.30 g/cm^3. Instability occurred in the first model, indicating that a density contrast of 0.15 g/cm^3 is too low. Slight instability occurred on the southwestern side of the model using a density contrast of 0.20 g/cm^3 which yielded an apparent depth of 5.1 km. Density contrasts of 0.25 and 0.30 g/cm^3 yielded depths of 4.0 and 3.3 km respectively. From these results it can be concluded that the apparent depth of the granite which is equivalent to the thickness of the bordering volcanic rocks is probably in the range of 3 to 5 km. The line of section, the gravity profile and the model derived using a density contrast of 0.25 g/cm^3 are shown in Figure 3. The residuals, which are the differences between the observed and the computed gravity profile, are also shown. Negative residuals of -8 and -2 mgal occur over the margins of the granite. These residuals can be eliminated if the granite is considered to be more basic at its margins, as found by Lovell (1967). A model was constructed with border facies 0.1 g/cm^3 denser than the core and using the method of Nagy (1964) its gravity effect was computed. The results are in better agreement with the observed profile (Figure 3).

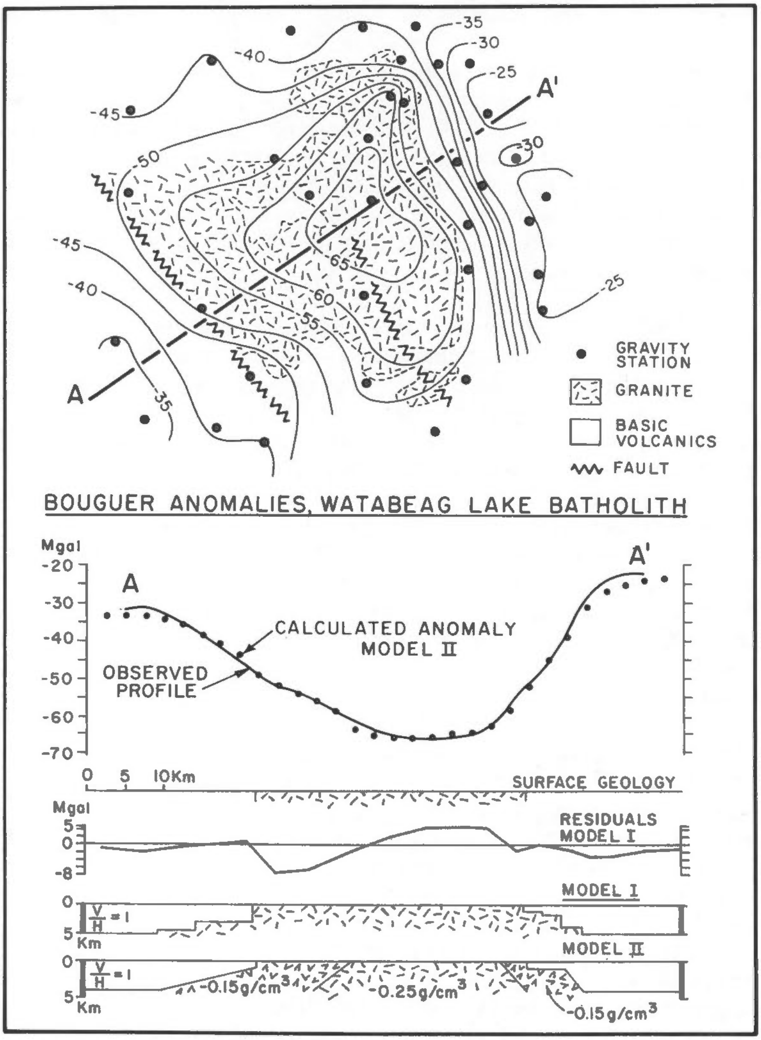

Figure 3. Gravity anomaly over the Watabeag Lake batholith.

Bernetz Batholith. The Bernetz batholith and its related gravity field are shown in Figure 4. Faessler (1934) traversed the eastern portion of this granite along the Laflamme River. He noted many variations in the composition of the intrusive rocks which include granodiorite, diorite, quartz gabbro, gabbro and hornblendite. The rocks are mainly coarse-grained and gneissic. Faessler recorded changes in texture and composition toward the contact with the Keewatin lavas. The gneissic rock grades

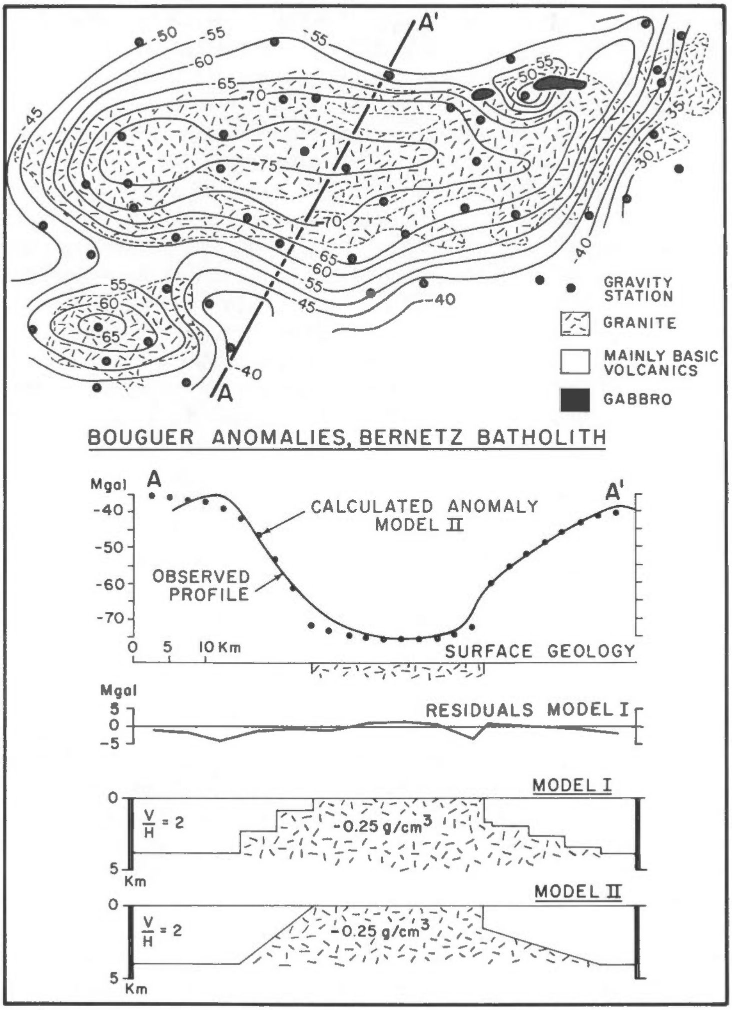

Figure 4. Gravity anomaly over the Bernetz batholith.

into hornblendite with a visible increase in the proportion of hornblende phenocrysts. In other areas the border facies is dioritic or gabbroic. Longley (1946) named the rocks of this area the Bernetz gneiss after the gneiss which occurs fairly uniformly throughout the mass; thin section examinations revealed the composition to be biotite-quartz diorite gneiss. The density of the gneiss estimated from volume percentages of the minerals recorded is 2.68 g/cm^3.

The gravity contours faithfully trace the outline of the batholith reaching minimum values of -75 mgal in the centre. A satellite stock to the southwest of the main mass underlies a local gravity minimum of -65 mgal. Although the granite is not uniform a homogeneous model was assumed in this preliminary analysis. The depth estimates will almost certainly require modification when detailed geological maps become available for this region. Using the same range of density contrasts as before, instability occurred using a density contrast of 0.15 g/cm^3, again implying that this value is too low. Density contrasts of 0.20, 0.25 and 0.30 g/cm^3 yielded apparent depths of 4.9, 3.8 and 3.1 km, respectively. In the absence of local density information for the surrounding rocks it is not possible to improve the estimate of the apparent depth. However, it is likely that these rocks have a density in the range 2.90 to 3.00 g/cm^3, which would favour the more shallow depths of less than 4 km. These depths may again be equated to the thickness of the greenstone belts adjacent to the gneiss. The gravity profile, residuals and the model derived using a density contrast of 0.25 g/cm^3 are shown in Figure 4, along with the results obtained using Nagy's method to calculate the gravity effect of a similar model with smoothed contacts.

Kenogamissi Lake Batholith. The Kenogamissi Lake batholith forms part of a much more extensive area of granitic rocks which occur to the northwest, west and south of the area shown in Figure 5. According to Todd (1923) a gneissic structure is well developed in the area east of Kenogamissi Lake. However, in other parts of the area massive granite, particularly biotite granite, is common. Small bosses of syenite occur throughout the mass.

The gravity contours follow the outline of the granite reaching minimum values of about -65 mgal (Figure 5). A local gravity high of -40 mgal cuts the low in the west and is underlain by an isolated area of Keewatin basic rocks. The sparse gravity data suggest that these rocks are related to outcrops further west although an intervening swamp obscures the surface geology. To the north of this high the granite contains an abundance of hornblende (Todd, 1923). The same method of interpretation was used along the gravity profile shown in Figure 5. Density contrasts of 0.15, 0.20, 0.25 and 0.30 g/cm^3 yielded apparent depths of 4.1, 3.0, 2.3 and 1.9 km, respectively. The model obtained using a density contrast of 0.25 g/cm^3 is shown in Figure 5. A smoothed version of the model showing the preferred depth of 3 km is also shown in Figure 5. Negative residuals over the margins of the granite are again probably related to more basic border facies.

Preissac-Lacorne Batholith. Dawson (1966) has made a comprehensive geological study of this batholith. The batholith consists of the Preissac, Lamotte and Lacorne massifs and other smaller stocks. Field relations and mineralogy suggest an intrusive magmatic origin. The rocks of the batholith range from leucoadamellite and granodiorite to intermediate monzonite and syenodiorite. Dawson attributes the intermediate facies to contamination of the granodioritic magma by assimilation of the country rock and he attributes the leucoadamellite to continued differentiation of the granodioritic magma.

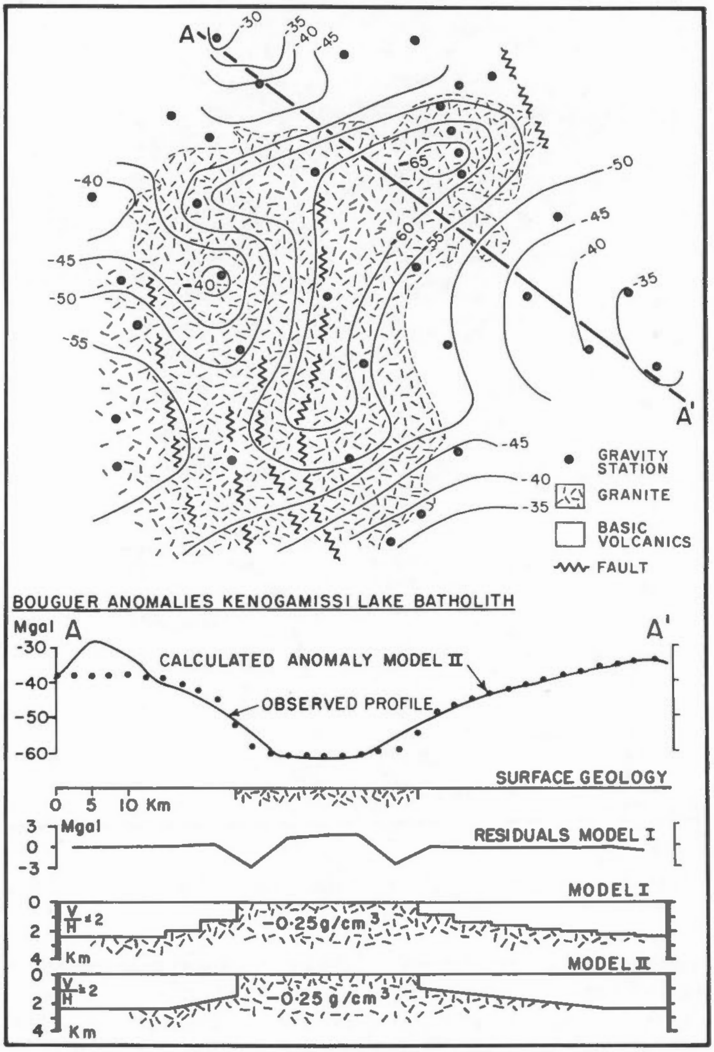

Figure 5. Gravity anomaly over the Kenogamissi Lake batholith.

Dawson obtained a thickness of 16,000 feet (almost 5 km) for the Lamotte and Preissac massifs from an analysis of gravity data and measured rock densities. The batholith is outlined by a large gravity low and local minima occur over the three main massifs: -70 mgal over the Preissac massif, -75 mgal over the Lamotte massif, and -80 mgal over the Lacorne massif (Figure 6). A gravity profile across the Lacorne massif is shown in Figure 6. A simple model with vertical sides 5 km deep, and

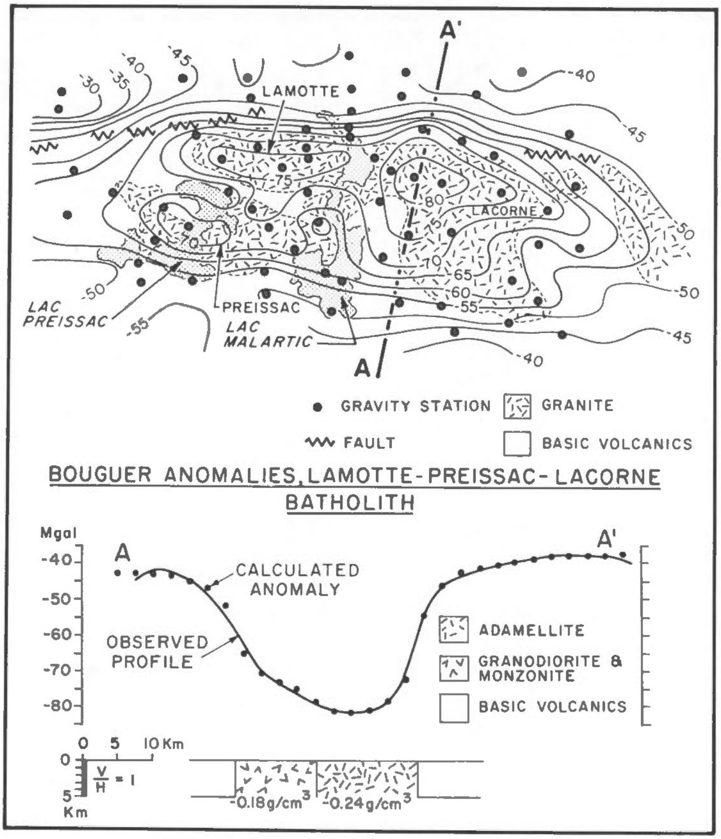

Figure 6. Gravity anomaly over the Preissac-Lacorne batholith.

densities corresponding to the adamellite (2.64 g/cm^3) and granodiorite-monzonite facies (2.70 g/cm^3) and the surrounding rocks (2.88 g/cm^3), has a computed gravity effect which is in good agreement with the Bouguer anomaly profile. The two-dimensional method described by Nagy (1964) was used to make this calculation. A more sophisticated model in three dimensions could be constructed from the detailed geological information available. However, such a study would require additional gravity stations more closely spaced and planned on the basis of the new geological map.

Palmarolle Granodiorite. The geology of the Palmarolle granodiorite is described by Cooke, et al. (1931) and Gussow (1937). Throughout most of the area only scattered outcrops project through a mantle of clay. The central parts of the intrusion consist of pink coarse-grained granodiorite, which contains a large proportion of quartz and plagioclase up to 30 per cent potash feldspar and some biotite (Gussow, 1937). The marginal phase is quartz diorite.

The gravity low, with minimum values of -70 mgal, which marks the Palmarolle intrusion appears to be offset to the west rather than centrally located over the mapped portion of the granite (Figure 7). However a westerly extension of the low is underlain by another intrusion on the shore of Abitibi Lake. It can be inferred from the gravity data that this satellite body is separated from the main mass by only a very thin veneer of Timiskaming sediments and basic volcanic rocks. A change in composition from the granitic rocks to a more basic phase can also be inferred from the gravity data in the eastern part of the mass. An easterly trending residual gravity high is reflected by a pronounced 'nose' in the gravity contours. This nose is in fact underlain by outcrops of coarse-grained gabbro or diorite (Cooke, et al., 1931). The rock is dark grey with hornblende and labradorite making up almost the whole rock in about equal quantities. A well-defined flow texture in the gabbro near the contact with the granite suggests that the gabbro may be a younger intrusion. The variability in the composition of the Palmarolle granodiorite could be mapped by detailed gravity stations. The intense low is underlain by the coarse-grained granite (2.70 g/cm^3), marginal facies of quartz diorite (2.75 g/cm^3) occur to the northeast and southeast and the nose of higher gravity values is underlain by the diorite-gabbro facies (2.85 g/cm^3). Using these assumed density values a simple model of four blocks with vertical sides all extending to a depth of 5 km have a combined gravity effect, calculated by Nagy's prism method (1966), which is very similar both in magnitude and pattern to that actually found over the granite (Figure 7). Two gravity profiles A and A$^{\prime}$ across the batholith and the three-dimensional model show that, although the magnitude of the anomaly and pattern show a good correspondence, refinements are required to improve the fit to the observed gradients. The reconnaissance data, however, do not warrant any further refinement of the model which merely illustrates how compositional variations can explain the gravity field in a reasonable way.

Round Lake Batholith. A sketch map of the Round Lake batholith and its related gravity low is shown in Figure 8. Parts of the batholith, particularly its margins, have been mapped and described by Cooke (1922), Moorhouse (1944), Lawton (1954 and 1957), Grant (1963) and Moore (1966). The batholith is a composite intrusion; it is characteristically more basic around the margins. Contacts with the Keewatin volcanic rocks are generally gradational and a gneissic texture is often developed marginally. The northern part of the batholith has been mapped by Moore (1966) who called the granite the Gross gneiss. A gneissic structure is developed between massive fine- to medium-grained granite and the surrounding volcanic rocks. Here the granite contains 10 to 15 per cent quartz, 10 to 15 per cent hornblende, 40 to 60 per cent plagioclase, and 15 to 20 per cent microcline. Cooke (1922) mapped the rocks around Round Lake as granite and syenite and noted that the margins of the syenite were more basic than the main mass, apparently due to digestion of the bordering basaltic tuff. This area was mapped later by Lawton (1954 and 1957), who named the mass north and west of Round Lake the Otto syenite stock. The medium- to coarse-grained syenite is mainly composed of perthitic feldspar with about 10 per cent pyroxene. Lawton also noted the more basic marginal phases and suggested a genetic relationship between the Otto stock and the Lebel syenite stock to the northeast. According to Lawton the Round Lake batholith is composed of two general rock types: an older quartz diorite - oligoclase granite facies of very uniform composition and a younger hornblende granite. The latter is massive and may grade into hornblende syenite. Southeast of Round Lake

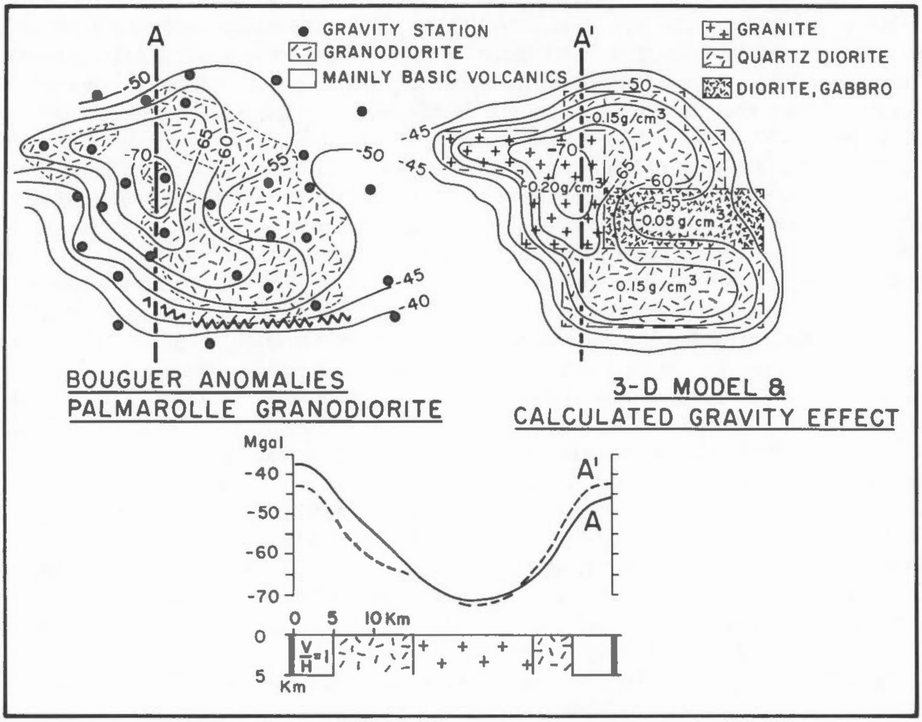

Figure 7. Gravity anomaly over the Palmarolle granodiorite.

the older granite intrudes Keewatin tuffs. Here the rock is a quartz-rich oligoclase granite, medium- to coarse-grained with a faintly foliate texture. Peripherally the batholith is extensively sheared and granulated. A vertical gneissic structure is present parallel to the contact and augen gneiss occurs at the contact where the shearing is most intense. The augen gneiss is also present at the eastern margin of the batholith where Grant (1963) described the gneiss as composed mainly of albite to albitic- oligoclase and quartz. Along the southern margin of the batholith to the southwest of Robillard Lake the granite appears to be rather uniform and is described by Moorhouse (1944) as a soda granodiorite rather than a granite. At the margin there is a widespread development of hybrid rocks, mainly diorites, some of intrusive origin, others formed by replacement; they grade into both granodiorite and typical recrystallized greenstones.

The variation in the composition of the batholith is reflected to some extent in the gravity anomaly. The lowest gravity values occur over the soda granodiorite in the eastern and central parts of the pluton. Higher values occur in the north where the hornblende granite and syenite occur and in the west. A gravity profile through the eastern part of the batholith and crossing the Otto syenite is shown in Figure 8.

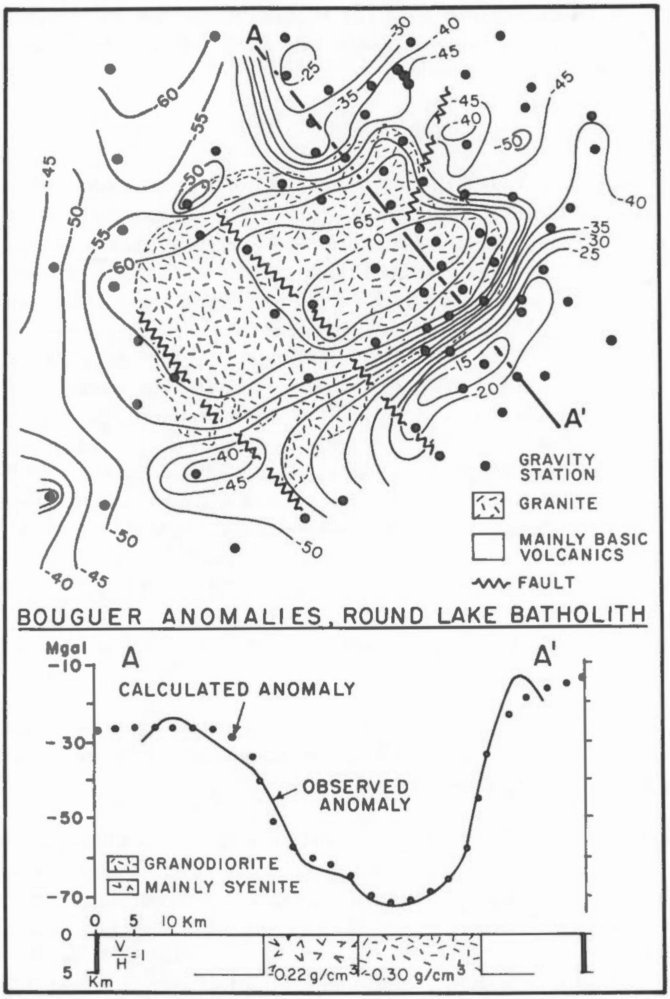

Figure 8. Gravity anomaly over the Round Lake batholith.

A simple two-dimensional model of the batholith is also shown in Figure 8. The gravity effect of the model was computed using the method of Nagy (1964); it corresponds fairly well with the observed profile, particularly over the soda granodiorite (2.65 g/cm^3) and over the southeastern contact with the Keewatin rocks (2.95 g/cm^3). The contacts were assumed to be vertical and if the density contrast extends downwards for 5 km an anomaly magnitude similar to that measured is obtained. A density difference of about 0.08 g/cm^3 between the soda granodiorite and the northern part of the batholith which includes the Otto syenite is related to a local increase in the anomaly of about 9 mgal within the batholith. The correspondence between calculated and observed profiles is not so close over the northwestern contact; residuals are of the order of 2 to 5 mgal, which implies a need for some refinement of the geometry of the model and the local density relations.

Positive Anomalies over the Volcanic Belts

Measurements of rock densities confirm that greenstones are denser than the surrounding rocks of the Canadian Shield which are predominantly of granitic composition. For this reason these belts are almost invariably characterized by positive gravity anomalies. Previous estimates from gravity data of the thickness of these belts range from 1 to 3 km (Garland, 1950), 4 to 7 km (Innes, 1960) and about 8 km (Grant, et al., 1965). These estimates are generally in agreement with estimates of stratigraphic thickness obtained from recent geological investigations. It should be emphasized that stratigraphic thicknesses are not equivalent to thickness estimates obtained from gravity data because the belts have often been subjected to severe folding and compression during orogeny and of course subsequent erosion has removed large amounts of the original pile. Goodwin (1966) has estimated that the total stratigraphic sequence of a volcanic-sedimentary pile is commonly 6 to 12 km thick. This result was obtained from a study of eight Archaean greenstone belts in the southern part of the Superior structural province. Baragar (1966) reported the following stratigraphic thicknesses for volcanic sections in the Shield: Yellowknife section - 13.6 km, Cameron River - 2 km, and in the Noranda area Lake Duparquet - 12 km, and Aiguebelle Township - 4 km. In some instances neither the top nor base of the section was identified.

As discussed in the previous section the apparent depths of the granites are equivalent to the thicknesses of adjacent greenstone belts. These estimates lie between 3 and 5 km in all the examples examined.

A section across the Preissac-Lamotte batholith and the Bernetz gneiss and the surrounding volcanic belts is shown in Figure 9. Using the program developed by Tanner (1967) for basin-shaped structures, models were obtained for the shapes of the volcanic belts. Density contrasts of 0.15, 0.20, 0.25 and 0.30 g/cm^3 were used. A density contrast of 0.15 g/cm^3 is too low a value as revealed by depth reversals which indicate instability of the system. Incipient instability occurs using 0.20 g/cm^3, which may be regarded as the minimum possible density contrast in this region. The model obtained assuming a density contrast of 0.25 g/cm^3 is shown in Figure 9. The volcanic rocks south of the Preissac-Lamotte batholith have a maximum thickness of 3.7 km and to the north the thickness is 3.2 km. This belt reaches its greatest depth (5.6 km) to the south of the Bernetz gneiss. The volcanic belt north of the Bernetz gneiss is 2.2 km thick. The residuals or differences between observed and computed gravity values are all less than 2 mgal and are plotted in Figure 9. In this method the anomalous mass is approximated by rectangular blocks of uniform density. Thin blocks appear over the margins of the batholiths where granite has been mapped at the surface. The method assumes a uniform density contrast and cannot at present include density changes within the granites themselves, which are in fact the cause of the higher gravity values at the margins of the granite. This is particularly true of the Preissac batholith which has a higher mean density than the Lamotte mass to the north. The

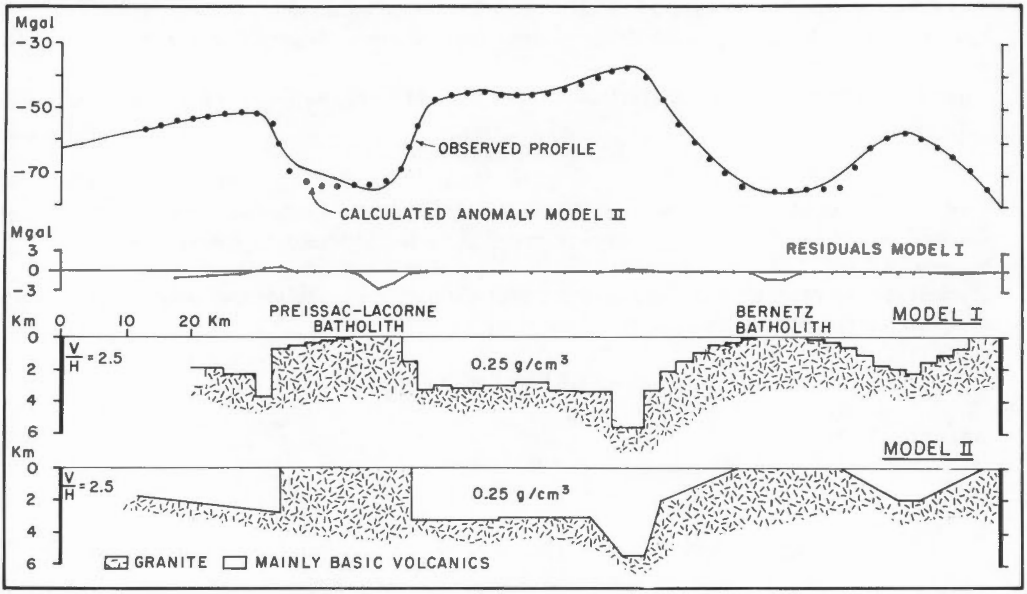

Figure 9. Gravity profile across the volcanic belts bordering the Preissac-Lamotte and Bernetz batholiths.

rectangular outline of the model was smoothed as shown in Figure 9 and the gravity effect of the model, which eliminates these erroneous thin marginal layers of volcanic material, was calculated using the method of Nagy (1964). The depths obtained are of course very similar to those of the first model. A uniform density contrast of 0.25 g/cm^3 was again assumed so that the residuals over the Preissac batholith are large (about 5 mgal). It has been shown in Figure 6 that a good fit to the observed values can be obtained using a higher density for the southern part of the Lacorne mass which has a somewhat similar density distribution. If the assumed density contrast is 0.30 g/cm^3 the volcanic belts are thinner, ranging from 2.8 km and 2.5 km south and north of the Preissac-Lamotte batholith to 4.2 and 1.8 south and north of the Bernetz gneiss. These estimates of thickness are in agreement with the thicknesses obtained from profiles (differing in location) across the batholiths as shown in Figures 4 and 6.

CONCLUSIONS

Differences in density and the distribution of granite batholiths and volcanic belts account for the major anomalies and complex pattern of the gravity field in the mining belt. On the assumption that the volcanic belts of the mining area are floored by granite, it can be concluded that these belts commonly extend to depths of less than 6 km. Particularly high gravity anomalies over some belts may indicate somewhat greater depths. Better estimates of depth could be obtained locally by detailed gravity traverses and rock sampling to obtain better values of local density contrasts. The gravimeter could be used effectively to map variations in composition within the granite batholiths, all of which appear to be composite intrusions. The granites extend to unknown depths, presumably to the base of the granitic layer of the crust.

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