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GRAVITY SURVEYS IN THE ALEXANDRIA AREA, EASTERN ONTARIO

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Bouguer Anomaly Map Alexandria Area, Ontario - Quebec . . . . . (in pocket)

GRAVITY SURVEYS IN THE ALEXANDRIA AREA, EASTERN ONTARIO

L.W. SOBCZAK

ABSTRACT: The results of 1700 gravity observations completed by the Dominion Observatory from 1945 to 1964 are presented in the form of a Bouguer anomaly map. Seven profiles are analyzed. The Bouguer anomalies are correlated with magnetic and geological information and the interpretation of the gravity data is based on rock density measurements. Two maps showing the computed first and second vertical derivatives of gravity are also presented.

Negative Bouguer anomalies are correlated with the Chatham-Grenville syenite stock and a similar intrusion at Mount Rigaud on the southern border of the Grenville-A subprovince. It is postulated that the negative anomaly near Plaisance indicates the presence of a similar intrusion below the Paleozoic cover. The Alexandria High, a positive residual Bouguer anomaly which extends from Lunenburg to Pointe-au-Chêne, may be explained by the presence of a basic lenticular body of thickness varying from 6000 to 9000 feet and width of 50,000 feet at a depth varying from 3000 to 5000 feet. The approximate thickness of the Grenville Series is 11,000 to 12,000 feet along the crest of the Alexandria High. The regional gravity gradient which increases from −30 mgal in the northwest to +10 mgal in the southeast of the area is correlated with a rise of over 3 kilometres (10,000 feet) of the Mohorovičić discontinuity.

RÉSUMÉ: L'auteur présente sous forme d'une carte d'anomalies de Bouguer les résultats de 1,700 observations gravimétriques effectuées par l'Observatoire fédéral de 1945 à 1964. Il analyse sept profils. Les anomalies de Bouguer sont mises en corrélation avec les données géologiques et magnétiques, et l'interprétation des données gravimétriques est fondée sur les mesures de la densité des roches. Il présente également deux cartes indiquant les premières et deuxièmes dérivées gravimétriques verticales.

Les anomalies négatives de Bouguer sont mises en corrélation avec le massif de syénite de Chatham-Grenville et une intrusion semblable au mont Rigaud à la limite sud de la sous-province Grenville-A. On croit que l'anomalie négative près de Plaisance indique la présence d'une intrusion semblable sous la couche Paléozoïque. L'Alexandria High, une anomalie positive résiduelle de Bouguer s'étendant de Lunenburg à Pointe-au-Chêne, peut être expliquée par la présence d'un dépôt basal lenticulaire d'une épaisseur de 6,000 à 9,000 pieds et d'une largeur de 50,000 pieds, à une profondeur variant de 3,000 à 5,500 pieds. L'épaisseur approximative de la série de Grenville varie de 11,000 à 12,000 pieds le long de l'arête de l'Alexandria High. Le gradient gravimétrique régional, qui s'échelonne de −30 milligals, au nord-ouest à 10 milligals au sud-est de la région, est mis en corrélation avec un exhaussement de plus de 3 kilomètres (10,000 pieds) de la discontinuité de Mohorovičić.

Introduction

A detailed gravity survey was completed in the Alexandria area covering some 2500 square miles in eastern Ontario, Canada (Figure 1). Gravity observations at intervals of one mile were made at bench marks and at the intersections of roads, railroads and streams. Road transport was used throughout the survey. The Bouguer anomalies were computed from these observations and the results were adjusted to the common datum of the primary network of gravity bases in Canada (Winter and Hamilton, 1965). The Bouguer anomaly values were plotted on a map at a scale of 1:50,000 which was photo-reduced to a scale of 1:125,000 (map in pocket).

Rock density measurements for 900 samples, aeromagnetic maps (published by the Geological Survey of Canada), first and second vertical derivatives of gravity and the geology of the area as described by various authors are employed as aids in the interpretation of the Bouguer anomalies.

Particular attention is given to the significance of:

(i) Negative residual gravity anomalies over the Chatham-Grenville Stock and Mount Rigaud.

(ii) A positive residual anomaly through the centre of the map area named the Alexandria High.

(iii) A regional anomaly in the southeast corner of the map area.

Descriptive Notes

Summary of the Regional and Control Gravity Work

The first substantial number of gravity observations in the Alexandria area was made with Humble and Atlas gravimeters by the Dominion Observatory during 1945 and 1948. These earlier observations were then linked to the Canadian primary network of gravity bases which provided a basis for adjusting this work to a common datum (Innes and Thompson, 1953). In 1951 and 1952, using North American 85 and Worden 44 gravimeters, additional gravity stations were established so that the regional gravity picture was completed at a scale of 4 miles to the inch (Thompson and Miller, 1958). In 1954 R.J. Uffen established a few gravity stations in the southeast corner of the Alexandria area during a gravity survey in Quebec (Thompson and Garland, 1957). In 1958 J.G. Tanner carried out additional gravity observations. From 1959 to 1964 the number of observations was increased by various field parties of the Dominion Observatory (Table 1).

Because of the high station density and considerable gravity relief, the Alexandria area was selected in 1959 as a region for vertical gradient field trials conducted by Lundberg and Hunting Exploration. A study of the vertical gradient of gravity was made by the Dominion Observatory. A method

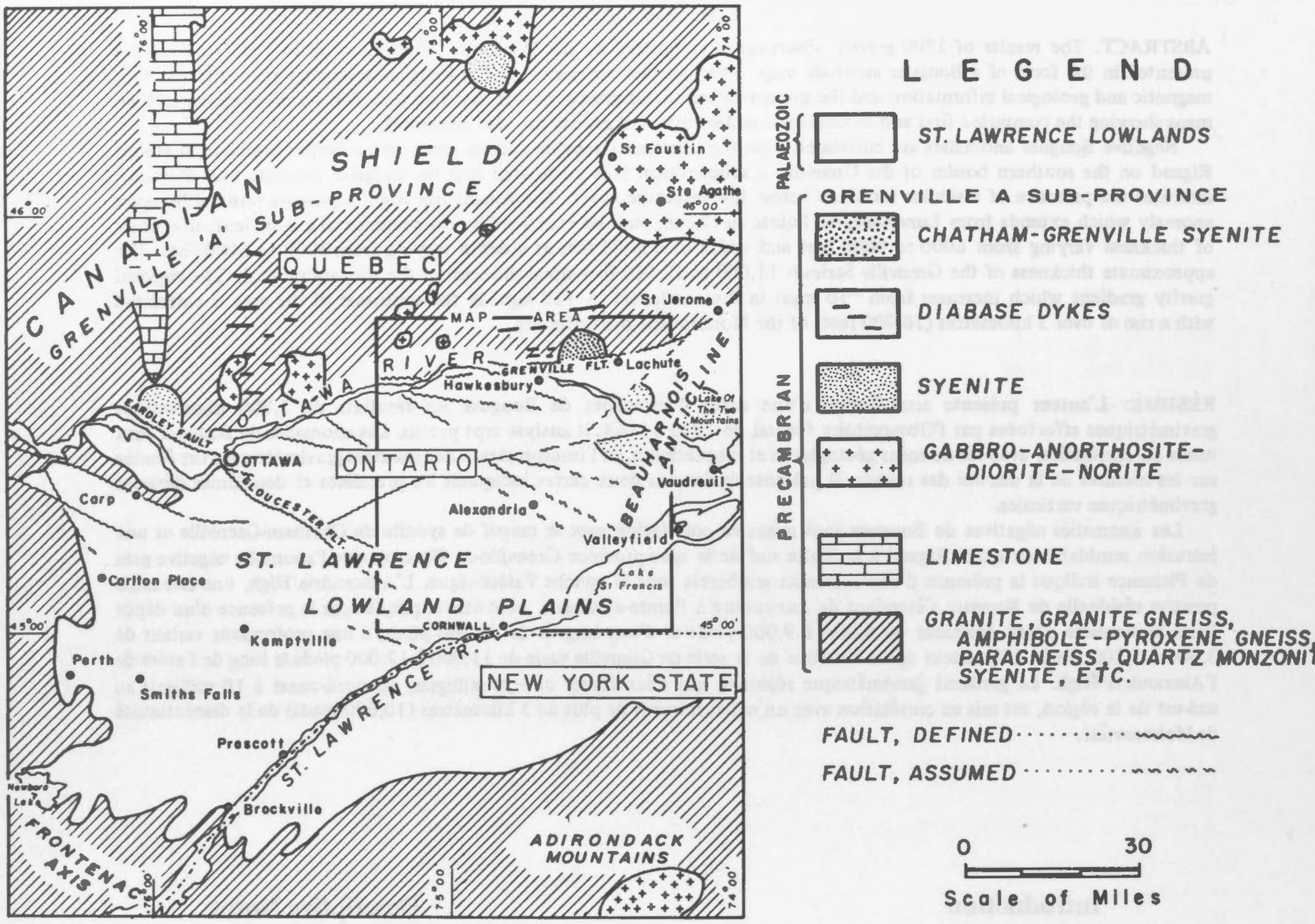

FIGURE 1. The location of the detailed gravity survey and the principal geological regions.

described by Baranov (1953) was programmed for the IBM 650 to give the vertical gradient at the surface of the ground or at any elevation. Elkins' (1951) method of computing the second vertical derivative was also programmed and this program is equally adaptable to other methods which use a similar technique. The method requires Bouguer anomaly values interpolated at the intersections of an adopted 5000-foot grid system but the gravity stations were not close enough to permit reasonable interpolation of the gravity values. Therefore since 1959 more effort to increase the station density has been concentrated in this area using temperature-compensated Worden and LaCoste-Romberg gravimeters.

As the regional gravity work was extended, a few necessary control stations were established by the method of forward looping (Nettleton, 1941) to reduce the data to a common datum. However, no effort was made to close or adjust this network until 1964. At this time a gravity survey was undertaken to establish control stations and regional stations at bench marks in Ontario and Quebec in the vicinity of Ottawa. Details of the network control stations are shown in Figure 2. This network was adjusted by a least-squares solution on the IBM 1620 by a method described by Hamilton (1964). All of the descriptions, the principal facts and the accuracies of the control stations are listed in an unpublished report (Winter and Hamilton, 1965).

Transportation

Road transport was used throughout the survey except in a small portion north of the Ottawa River between Pointe-au-Chêne and Fasset where a Bell G-2A helicopter was used for a few hours in 1963 to reach inaccessible areas.

Accuracy of the Measurements

Free-air and Bouguer anomalies have been computed. Normal gravity values were obtained from the International Gravity Formula (1930) and a mean rock density of 2.67 gm/cm^3 was used in the Bouguer reduction.

Observational errors in the gravity measurements represent a certain amount of unreliability in the computed anomaly values. The gravity observations were made with many instruments (Table 1) which contribute observational errors ranging from a few hundredths of a milligal for the more modern LaCoste-Romberg gravimeters to a tenth of a milligal for the older Atlas and Humble gravimeters. Small errors of 0.03 mgal due to drift and transport are possible in the observations.

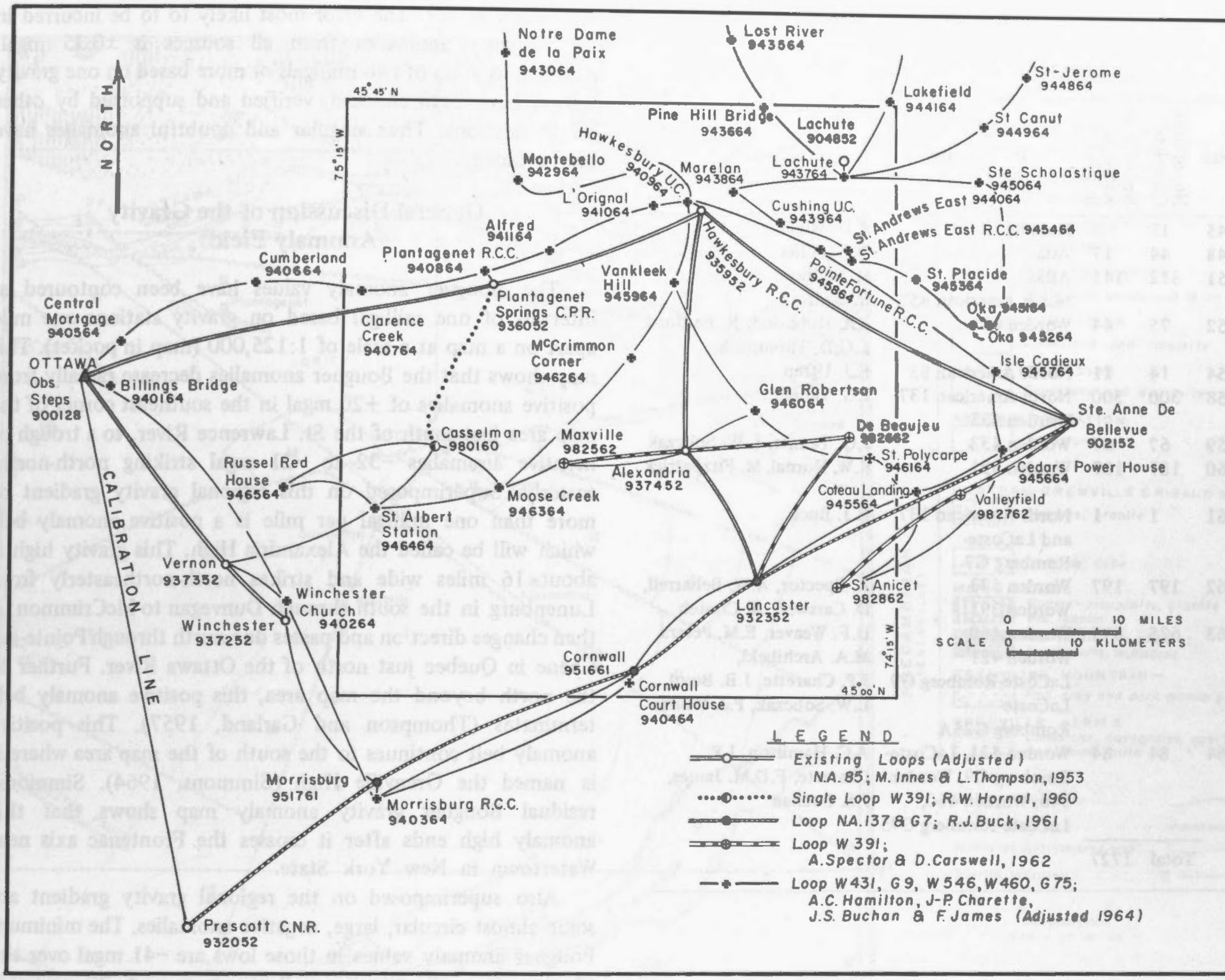

FIGURE 2. Control stations and ties in the Alexandria area.

Most of the gravity measurements were made at bench marks, railway stations, railway crossings and road crossings, where precise elevations are known. These elevations are accurate to the nearest foot which represents a maximum error in the elevation reduction of ±0.03mgal. The remaining elevations were determined using Wallace and Tiernan altimeters which yield elevations accurate to ±5 feet. This represents an error in the elevation reduction of ±0.3 mgal.

The latitudes and longitudes of all the stations have been scaled to a tenth of a minute from maps at a scale of 1:50,000. The maximum error in the normal gravity values from scaling the latitudes would be ±0.15 mgal.

The control network adjustment (Hamilton, 1964, Figure 2), adjusts the observed gravity differences between control points by a least-square method so that the sum of the gravity differences around any one loop is zero. The maximum variation between the unadjusted and adjusted gravity differences with any one of the gravity instruments used during any one set of observations is 0.12 mgal. The standard deviation of the residuals of the loops is ±0.05 mgal.

Terrain Effects

Terrain corrections have not been applied to the Bouguer anomalies as most of the area is relatively flat with a range in elevation of 125 to 375 feet. Thus terrain corrections would probably be less than 0.1 mgal. Most of the gravity stations north of the Ottawa River are in more rugged terrain with a range in elevation of 125 to 1300 feet. In this area the terrain correction was computed for a station on Maholey Lake which is quite remote, and which lies in a depression with an elevation change from 175 to 1200 feet. The correction for this station as determined by the method outlined by Hammer (1939), is less than 0.4 mgal, which probably represents the largest terrain correction in the area for the existing gravity stations.

Summary of Errors

It is difficult to assess these errors and at times difficult to assign a probable error to a station because of all the variables

Table 1

SUMMARY OF FIELD WORK

Year	No. of Stns. Completed	No. of Stns. Retained in 1964	Instruments	Observer
1945	13	3	Humble	A.H. Miller
1948	44	17	Atlas	A.H. Miller
1951	312	141	Atlas North American 85	M. Sullivan R. Bedford
1952	75	44	Worden 44	J.A. Robinson, R. Bedford, L.G.D. Thompson
1954	14	11	North American 85	R.J. Uffen
1958	300	300	North American 137 Worden 433	J.G. Tanner
1959	67	67	Worden 433	J.G. Tanner, L.W. Sobczak
1960	187	187	Worden 391	R.W. Hornal, M. Fitzpatrick
1961	1	1	North American 137 and LaCoste-Romberg G7	R.J. Buck
1962	197	197	Worden 573 Worden 391	A. Spector, A.W. Beharrell, D. Carswell, A. Conteh
1963	675	675	Worden 460 Worden 421 LaCoste-Romberg G9 LaCoste-Romberg G25A	D.F. Weaver, E.M. Peters M.A. Archibald, J.P. Charette, J.B. Boyd, L.W. Sobczak, P.J. Winter
1964	84	84	Worden 431, LaCoste-Romberg G9, Worden 546, Worden 460, LaCoste-Romberg G75	A.C. Hamilton, J.P. Charette, F.D.M. James, J.S. Buchan
	Total	1727		

Table 2

SUMMARY OF OBSERVATIONS

(i) Total number of observations 1400
(ii) Arithmetic mean, Bouguer anomalies, −13.8 mgal
(iii) Arithmetic mean, free-air anomalies −4.9 mgal
(iv) Arithmetic mean, elevations 260.5 feet
(v) Maximum elevation of 927 feet with a Bouguer anomaly of −17.3 mgal for station number 1227-60 at latitude 45° 44.6′ north and longitude 74° 31.3′ west.
(vi) Minimum elevation of 81 feet with a Bouguer anomaly of −25.5 mgal for station number 14423-63 at latitude 45° 32.2′ north and longitude 74° 18.9′ west.

Type of Anomaly	Amplitude of Anomaly	Stn. No.	Position Lat.	Position Long.	Elev. (feet)	Magnitude (mgal)
Bouguer	Maximum	5345-54	45° 02.3	74° 18.9′	180	19.7
Bouguer	Minimum	12232-60	45° 39.1	74° 27.0′	259	−41.1
Free-air	Maximum	8646-63	45° 05.2′	74° 15.8	178	29.4
Free-air	Manimum	12232-60	45° 39.1	74° 27.0	259	−32.3

mentioned earlier. The error most likely to to be incurred in the Bouguer anomalies from all sources is ±0.35 mgal. Anomalous areas of two milligals or more based on one gravity station have been checked, verified and supported by other gravity stations. Thus singular and doubtful anomalies have been avoided.

General Discussion of the Gravity Anomaly Field

The Bouguer anomaly values have been contoured at intervals of one milligal based on gravity stations one mile apart on a map at a scale of 1:125,000 (map in pocket). This map shows that the Bouguer anomalies decrease radially from positive anomalies of +20 mgal in the southeast corner of the map area just south of the St. Lawrence River, to a trough of negative anomalies −32 to −21 mgal striking north-northeasterly. Superimposed on this regional gravity gradient of more than one milligal per mile is a positive anomaly belt which will be called the Alexandria High. This gravity high is about 16 miles wide and strikes north-northeasterly from Lunenburg in the south through Dunvegan to McCrimmon; it then changes direction and passes due north through Pointe-au-Chêne in Quebec just north of the Ottawa River. Further to the north beyond the map area, this positive anomaly belt terminates (Thompson and Garland, 1957). This positive anomaly belt continues to the south of the map area where it is named the Grenville High (Simmons, 1964). Simmons' residual Bouguer gravity anomaly map shows that this anomaly high ends after it crosses the Frontenac axis near Watertown in New York State.

Also superimposed on the regional gravity gradient are some almost circular, large, negative anomalies. The minimum Bouguer anomaly values in those lows are −41 mgal over the Chatham-Grenville Stock near Brownsburg, and −30 mgal near Plaisance. In the northwest corner of the map there are some smaller irregular positive residual anomalies such as the one near Burkes Corners of −16 mgal in a more negative gravity field of −23 mgal.

Most of the above mentioned anomalies were detected earlier but their limits were not defined because of the lower station density. Some of the larger anomalies were discussed in general terms by Thompson and Miller (1958). Here an attempt is made to discuss fully these intermediate anomalies in the light of recent work in this area.

Table 2 summarizes some pertinent data in the Alexandria area. Reoccupied gravity stations and new stations established very close to existing stations were not used in calculating the arithmetic means listed in Table 2.

General Geology

Introduction

The Alexandria area is located within the St. Lawrence Lowland between two of the main physiographic and geological regions of Canada, the Canadian Shield on three sides,

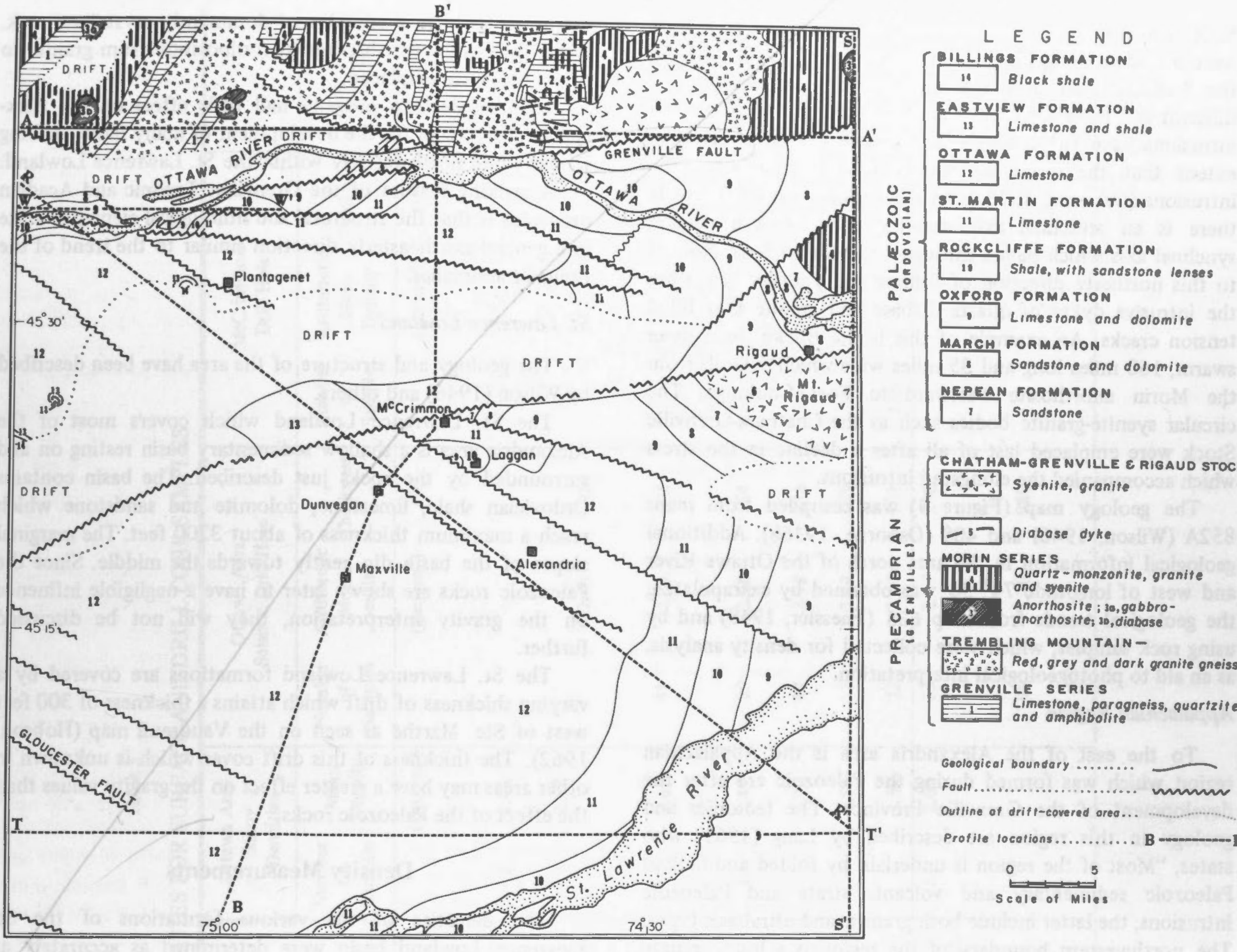

FIGURE 3. Geological sketch map and the location of profiles A-A', R-R', S-S', M-M', B-B', T-T', W-W'.

and the Appalachian region in the east (Stockwell, 1963). The Canadian Shield in turn is divided into six provinces which were determined by the ages of the rocks (Leech, *et al.* 1963). This age determination has also indicated four main orogenic periods in the Precambrian era the Kenoran, the Hudsonian, the Elsonian and the Grenville, at around 2500, 1700, 1350 and 950 million years ago, respectively (Stockwell, 1965). The Grenville Province and orogeny are of the greatest interest in this interpretation since the Grenville Province underlies and nearly surrounds the St. Lawrence Lowland. A short gelogical summary is presented for the Grenville Province, the Appalachian region and the St. Lawrence Lowland.

Grenville Province

Osborne and Morin (1962) have subdivided the Grenville Province into two subprovinces A and B mainly on the basis of differences in tectonic patterns, types of plutonites and grades of metamorphism. The Grenville B subprovince will not be described here as the gravity survey did not extend into this area. The Grenville A subprovince, which includes the type locality for the Grenville Series, is dominated by northerly structural trends first recognized by Logan (1863). This subprovince is much simpler geologically than the Grenville B subprovince.

The oldest rocks in the Grenville A subprovince are the Grenville Series consisting of a sequence of rocks with amphibolite at the base of the series followed by quartzite which grades into sillimanite-garnet gneiss which in turn passes into crystalline limestone. An analysis of the amphibolites from Shawinigan Falls area 160 miles east of Ottawa, suggests that they are metamorphosed basic tuffs and flows (Osborne, 1936a). Near the top of the syncline at Shawinigan Falls, metasedimentary rocks 3000 to 5000 feet thick are present above the amphibolite.

The Grenville Series is intruded by many igneous rocks ranging in composition from granite to gabbro. The Trembling Mountain gneiss, a leucocratic, rose coloured, granite gneiss (Figure 3), is the oldest of the intrusive rocks in the area. The structurally concordant relationships indicate that this granite gneiss was intruded during folding (Osborne, 1936a). The Morin

Series which range in compositon from anorthosite to granite were intruded along planes parallel to the regional strike. In the Lachute map area the determination of structure is difficult and metamorphism has obliterated any textures. The intrusions have cut through the Grenville Series to such an extent that the series are merely relics left between the intrusions (Osborne, 1936a). In the region west of Grenville there is an anticlinal axis trending north with a parallel synclinal axis which passes through Grenville to Weir. Normal to this northerly direction of folding and younger in age are the intrusive dykes of quartz diabase and granite that filled tension cracks. An example of this is the Buckingham dyke swarm, 180 miles long and 35 miles wide which extends from the Morin anorthosite westward to Fort Coulonge. The circular syenite-granite bodies such as the Chatham-Grenville Stock were emplaced last of all after a decline in the stress which accompanied the elongated intrusions.

The geology map (Figure 3) was compiled from maps 852A (Wilson, 1946) and 408 (Osborne, 1936b). Additional geological information in the area north of the Ottawa River and west of longitude 74° 50′ was obtained by extrapolating the geological trends from map 638 (Faessler, 1948) and by using rock samples, which were collected for density analysis, as an aid to photogeological interpretation.

Appalachian Region

To the east of the Alexandria area is the Appalachian region which was formed during the Paleozoic era after the development of the Grenville Province. The tectonics and geology in this region are described by Lang (1961) who states, "Most of the region is underlain by folded and faulted Paleozoic sedimentary and volcanic strata and Paleozoic intrusions; the latter include both granitic and ultrabasic types. The northwestern boundary of the region is a long, arcuate fault or zone of faults extending from Lake Champlain at least as far as the Gulf of St. Lawrence. East and south of this line the strata have been folded and faulted by successive periods of orogeny, along axes that strike northeasterly. Thus strata of different kinds and ages, and belts of intrusive rocks form northeasterly trending bands or lineaments. Three principal periods of orogeny – called the Taconic, the Acadian, and the Appalachian – have been recognized. The Taconic occurred at the close of the Ordovician, the Acadian during the Devonian, and the Appalachian at the close of the Paleozoic."

Folding and thrust faulting of the Taconic orogeny are fairly widespread in areas to the east of the Alexandria area such as eastern New York, Vermont and southeastern Quebec. During the Ordovician period the area south of the Ottawa River was inundated by Epiric seas in which sediments of the St. Lawrence Lowland were deposited, as can be seen on the Ordovician tectonic map (Eardley, 1962). The Frontenac axis of the Canadian Shield developed during this time and formed the southeastern boundary of the St. Lawrence Lowland (Figure 1).

In Quebec the Taconic structures were eroded prior to the Acadian orogeny, during which the strata were further deformed to form a complex of dominantly crystalline rock. Large batholiths, which range in composition from granite to peridotite, were emplaced.

The Appalachian orogeny had little effect on the Alexandria area except for the development of many faults striking westerly and northwesterly within the St. Lawrence Lowland.

A striking feature of the Grenville, Taconic and Acadian orogenies is that the structural and lithological elements strike in a general northeasterly direction similar to the trend of the Bouguer anomalies.

St. Lawrence Lowland

The geology and structure of the area have been described by Wilson (1946) and others.

The St. Lawrence Lowland which covers most of the Alexandria area is a shallow sedimentary basin resting on and surrounded by the rocks just described. The basin contains Ordovician shale, limestone, dolomite and sandstone which reach a maximum thickness of about 3200 feet. The marginal slopes of the basin dip gently towards the middle. Since the Paleozoic rocks are shown later to have a negligible influence on the gravity interpretation, they will not be discussed further.

The St. Lawrence Lowland formations are covered by a varying thickness of drift which attains a thickness of 300 feet west of Ste. Marthe as seen on the Vaudreuil map (Hobson, 1962). The thickness of this drift cover which is unknown in other areas may have a greater effect on the gravity values than the effect of the Paleozoic rocks.

Density Measurements

The densities of the various formations of the St. Lawrence Lowland basin were determined as accurately as possible using samples from drill holes and from the surface. These results were compared with those obtained earlier by Saxov (1956) and Simmons (1964). The densities of Precambrian rock samples which were taken from outcrops in the survey area north of the Ottawa River in the Grenville Province were also determined. A detailed sample traverse was made along Profile A-A′ (Figure 5). Considering the complexity of the Precambrian rocks it is difficult to determine average densities. An estimate of the density of the drift and overburden of sand, clay and gravel was obtained using the seismic information for the Vaudreuil map area (Hobson, 1962) and the velocity-porosity, porisity-density curves of Nafe and Drake (1957).

The densities of nearly 880 samples collected within the Ottawa Valley representing both the Precambrian and Paleozoic rocks have been summarized in Tables 3 and 4. Table 3 compares the number of samples and the arithmetic mean of the densities for the various Ordovician formations as obtained earlier by Saxov (1956) from formation outcrops within the Ottawa area and recently by the author from two drill holes. Densities of the drill core samples were determined at five-foot intervals from 1975 feet of core for the seismic

Table 3

ROCK DENSITIES FOR SURFACE AND DRILL CORE SAMPLES

Era	Period	Sub-Epoch	Formation	Sub-Divisions	Ottawa Area Saxov Densities: Number of Samples	Ottawa Area Saxov Densities: Mean Density	Ottawa Area Seismic Drill Hole: Number of Samples	Ottawa Area Seismic Drill Hole: Arithmetic Mean Density	Ottawa Area Seismic Drill Hole: Thickness	McCrimmon Drill Hole: Number of Samples	McCrimmon Drill Hole: Arithmetic Mean Density	McCrimmon Drill Hole: Thickness	A.E. Wilson Thickness
						(gm/cm^3)		(gm/cm^3)	(ft)		(gm/cm^3)	(ft)	(ft)
Paleozoic	Ordovician	Richmond	Queenston and Russell	Red shale Grey shale									100
		Lorraine	Carlsbad	Grey shale and rusty shale	12	2.62							550
		Gloucester	Billings	Black shale	8	2.62							260-300
			Eastview	Limestone and shale				Drift	45				20 at Ottawa thins to E
		Trenton and Black River	Ottawa	Limestone	10	2.69	41	2.64	225		Drift		700
		Chazy	St. Martin	Limestone		2.69					Drift	46	20-Ottawa 155-Alexandria
			Rockcliffe	Shale and sandstone lenses	10	2.49	29	2.58	154		Lost	129+	140-150
		Beekman-town	Oxford	Dolomite and limestone	13	2.72	47	2.72	233	106	2.78	594	240 at Ottawa incr. to E
			March	Interbedded sand-stone and dolomite	4	2.58	5	2.62	29	38	2.70	207	25-30
			Nepean	Sandstone	4	2.52	22	2.57	101	156	2.56	849+	500 known max.
Precambrian			Grenville	Syenite, marble quartzites, granites, granite gneiss, amphibole gneiss,	51	2.66	33	2.47	208				
				quartz monzonites, chlorite sericite schist			196	2.76	980				

Table 4

ROCK DENSITIES WITHIN THE VICINITY OF PROFILE A-A′.
(Precambrian Era)

Area	Description	Number of Samples	Mean Density (gm/cm^3)	Mean Density of Zones (gm/cm^3)	Mean Density of Zones (gm/cm^3)
Zone 1	Light coloured granites and syenites	13	2.61	2.61	
Zone 2	Red and dark granite and gneiss marble	16	2.74	2.72	2.68
Zone 3	Granite gneiss	4	2.64		
Zone 4	Amphibole gneiss	4	2.80	2.71	
Zone 5	Granite gneiss	5	2.63		
Zone 6	Granites and syenites	56	2.65	2.65	2.65
Alexandria High	Granite gneiss and marble Paragneiss amphibole and granite gneiss	9	2.85	2.85	2.85
Zone 7 Chatham-Grenville Stock	Syenite and granite	21	2.58	2.58	2.58
Zone 8	Granite gneiss Quartz monzonite Granite marble	21	2.65	2.65	2.65
Zone 9 Mount Rigaud	Syenite and granite	47	2.61	2.61	2.61

drill hole at the Dominion Observatory and from 1825 feet of core from McCrimmon, Ontario. Figure 4 shows the amount of scattering in density values for the seismic drill hole. It is readily seen from Table 3 that the average densities obtained from the core are somewhat greater than those obtained from surface samples with the exception of the Ottawa-St. Martin limestone formations. This table also indicates a lateral density variation from Ottawa to McCrimmon for the Oxford and March formations of limestone dolomite, interbedded sandstone and dolomite; but the Nepean Formation of sandstone seems to be of uniform density. The densities of the Paleozoic formations also agree with those determined for northern New York (Simmons, 1964).

The densities obtained for some of the Precambrian rocks taken along Profile A-A′ are shown graphically (Figure 5) and summarized according to arbitrary zones in Table 4. This table represents nearly 200 of the 420 Precambrian rock samples. The over-all average density of the Precambrian rocks excluding the samples taken from the syenite-granite intrusions such as the Chatham-Grenville Stock and Mount Rigaud and the gabbro intrusions, is 2.67 gm/cm^3, slightly larger than Saxov's density of 2.66 gm/cm^3 determined for the Ottawa area. The average density varies along profile A-A′ (Figure 5) from 2.68 gm/cm^3 in zones 1 to 5 to an average density of 2.65 gm/cm^3 in the east. In addition there are some small basic intrusions of gabbro to the north of the area of the profile which range in density from 2.91 to 3.08 gm/cm^3. Amphibolite in the Shawinigan Falls area has an average density 2.90 gm/cm^3 (Osborne, 1936a). There is also a small outcrop within zone 6 of paragneiss and amphibole-granite gneiss which yields an average density of 2.85 gm/cm^3. Figure 4 shows that the upper 300-foot section of Precambrian rocks have very low densities which gradually increase at the rate of 0.16 gm/cm^3 per 100 feet to an average density of 2.76 gm/cm^3. The standard deviation for the observed and calculated density values in this weathered zone is ±0.06 gm/cm^3.

Near Alexandria the average density of the Paleozoic rocks weighted according to formation thickness is the same as the average density of 2.65 gm/cm^3 of the Precambrian rock on the easterly side of Profile A-A′. Also this average density is only slightly less than the over-all average density of the Precambrian rocks of 2.67 gm/cm^3. This same conclusion was reached by Brant (1943) who states, "The densities expected for the Paleozoic rocks in southwestern Ontario are the same as may be expected for the densities of the Precambrian rocks." The region to the north of the Alexandria area, outlined in Figure 1, has been sparsely sampled (Thompson and Garland, 1957). Their average density determined from 36 samples representing the Grenville Series of crystalline limestone, the Trembling Mountain granite gneiss and the members of the Morin Series of granite, syenite and quartz monzonite other than anorthosite is 2.75 gm/cm^3, which is considerably larger than that determined along Profile A-A′, but much the same as that determined by Simmons (1964).

An average density determination was made for the Chatham-Grenville Stock which consists mainly of syenite. The densities for this stock ranged from 2.52 to 2.64 gm/cm^3, yielding an average density of 2.58 gm/cm^3. Next the

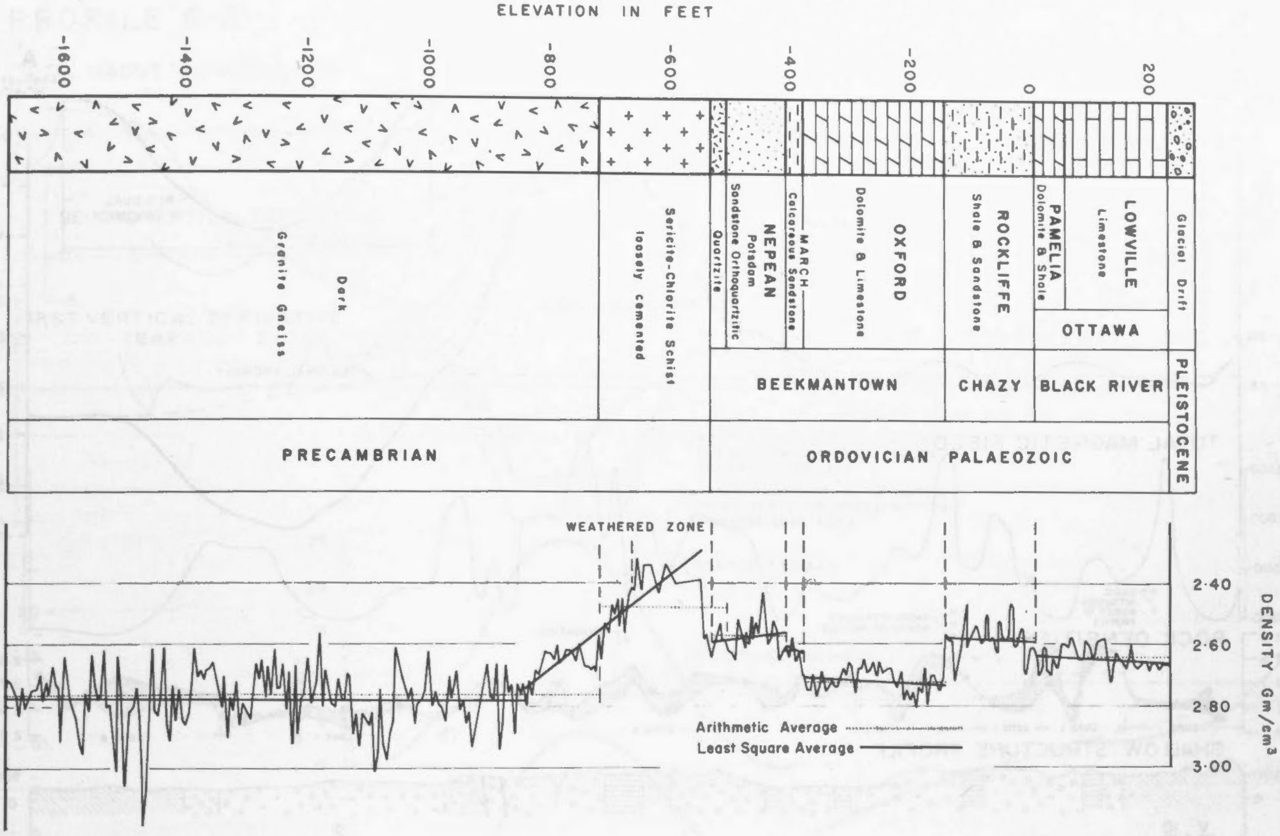

FIGURE 4. Measured grain densities on the drill core at five-foot intervals for the seismic drill hole at Ottawa.

granite-syenite intrusion of Mount Rigaud was sampled and the average density was found to be 2.61 gm/cm^3 from 47 samples. These density values are considerably lower than those determined by Simmons (1964) who obtained a bimodal density distribution of 2.68 and 2.77 gm/cm^3.

The density of the overburden obtained from seismic velocities (Hobson, 1962) and velocity-porosity, porosity-density curves (Nafe and Drake, 1957) was 1.80 gm/cm^3. This value could be in considerable error.

Correlation of the Bouguer Anomalies With the General Geology

Introduction

There is a good correlation between Bouguer anomalies and Precambrian geology when it is known, but most of the area is covered by Paleozoic strata. Because the average density of the Paleozoic strata is much the same as the average density of the surface Precambrian rocks, little or no gravity effect is indicated. Thompson and Miller (1958) state that the Paleozoic cover over most of the area appears to have little effect on the regional gravity anomalies. Brant (1943) has shown that the Paleozoic columns do not give rise to gravity anomalies greater than 0.3 mgal. The circular negative anomalies are associated with syenite-granite intrusions such as the Chatham-Grenville Stock and Mount Rigaud. Evidence obtained from surface density sampling along profile A-A′ (Figure 5) shows that the Alexandria High is not related to the surface Precambrian rocks. There are some small Bouguer anomaly highs in the northwestern corner of the map which are directly related to exposed basic rock intrusions; for example, the gabbro-diabase intrusion near Burkes Corners. The regional gradient which increases at a rate of 1 to 1.5 mgal/mile from a minimum of −30 mgal to +10 mgal at the southeast corner is explained by a slight rise of the Mohorovičić discontinuity of 3 to 3.3 kilometres from the general level of about −36 kilometres (Simmons, 1964).

To clarify the interpretations discussed in the following sections, the profiles A-A′, R-R′, S-S′ and M-M′ of Figures 5, 6, 7 and 8 have been constructed to relate geological and gravity data. The profile locations are shown on the geological map, Figure 3. Figure 5 shows the variation in density in the surface Precambrian rocks and compares the magnetic variation with the gravity variation. Profiles B-B′ and T-T′ of Figures 9 and 10 further delineate the Alexandria high. The anomalies in the profiles have been separated by smoothing by eye into regional and residual anomalies. The residual anomalies are explained by surface and near surface masses whereas the regional anomaly is attributed to variation in the depth of the Mohorovičić discontinuity. The gravitational effect of two-dimensional bodies has been computed by using a segment chart (Hubbert, 1948) for preliminary calculations and finally processed on the IBM 1620 using a line integral method

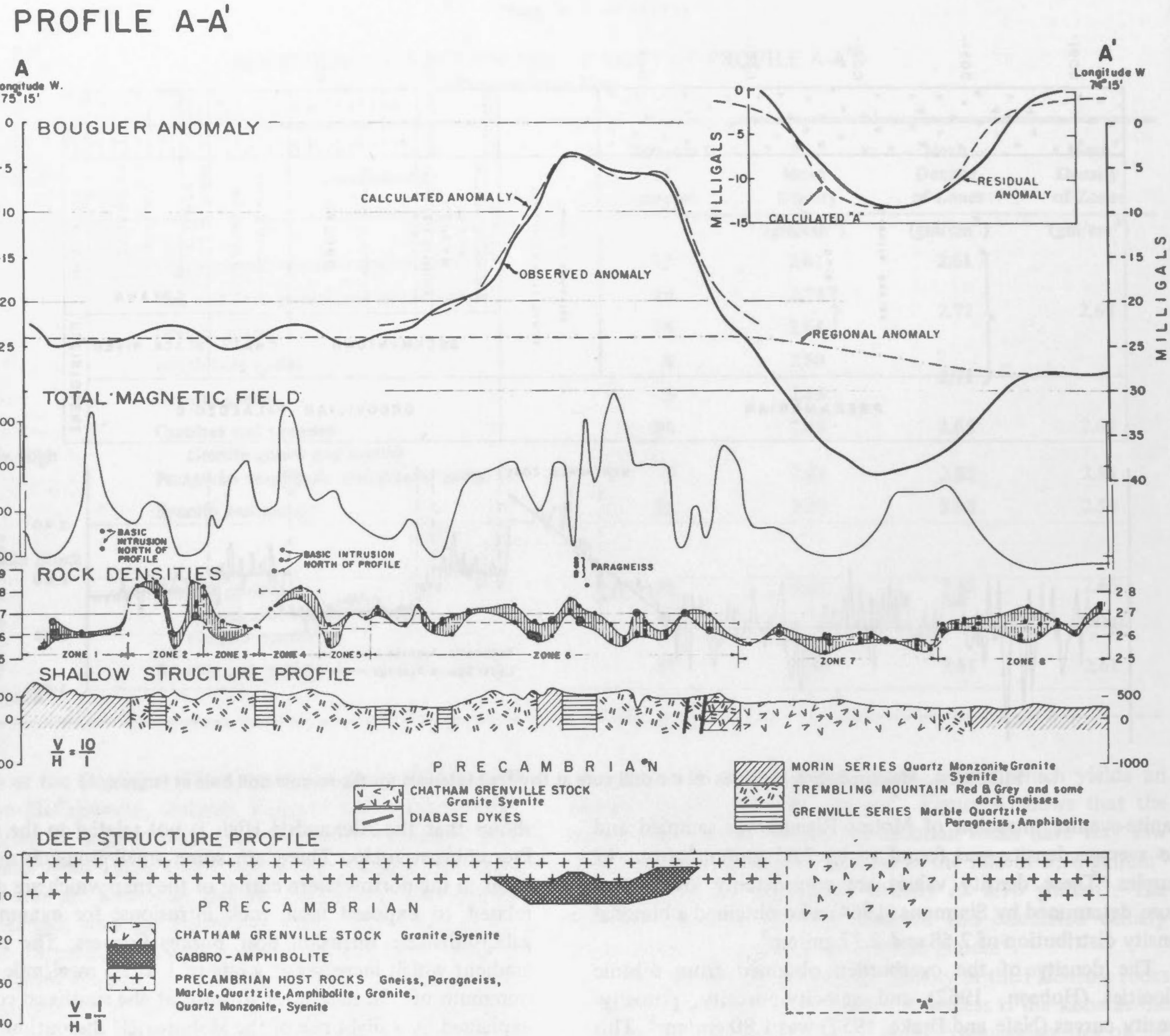

FIGURE 5. Profile A-A′ showing the observed and calculated Bouguer anomalies, magnetic anomalies, densities and geological structures.

(Morgan and Grant, 1963; Nagy, 1964). For a three-dimensional body such as the Chatham-Grenville Stock, anomalies have been computed using a program which calculates the effect of a right circular cylinder (Nagy, 1965).

Syenite-Granite Intrusions

Chatham-Grenville Stock. A residual Bouguer anomaly low of −13 mgal was obtained from four profiles taken across the Chatham-Grenville Stock. This anomaly is related to the intrusion of syenite and granite, which has a density lower than the surrounding rocks. The density contrast between this stock and the host rocks is −0.07 gm/cm^3 as determined from surface density sampling (Table 4 and Figure 5). Different methods of calculating the shape of the stock were tried.

A close approximation to the residual curve was obtained from a right circular cylindrical model with a radius of 20,000 feet that closely approximated the radius of the existing outcrop, and a depth of 37,000 feet (Figure 5). A comparison between the calculated and observed anomalies indicates that this cylinder is either dipping to the east or the southern part of the body is displaced to the east. The latter is quite possible since there is a fault (Grenville Fault) through the centre of the body. However, the southern half of the stock is covered by Paleozoic sediments which obscure any evidence of the true field relations.

Mount Rigaud. The Mount Rigaud Bouguer anomaly low of −30 mgal which has a residual anomaly of −7 mgal, is neither as clearly defined nor as regular as the Bouguer anomaly low over the Chatham-Grenville Stock. The Mount Rigaud low is related to a syenite and granite intrusion outcropping along the Beauharnois anticline. The density

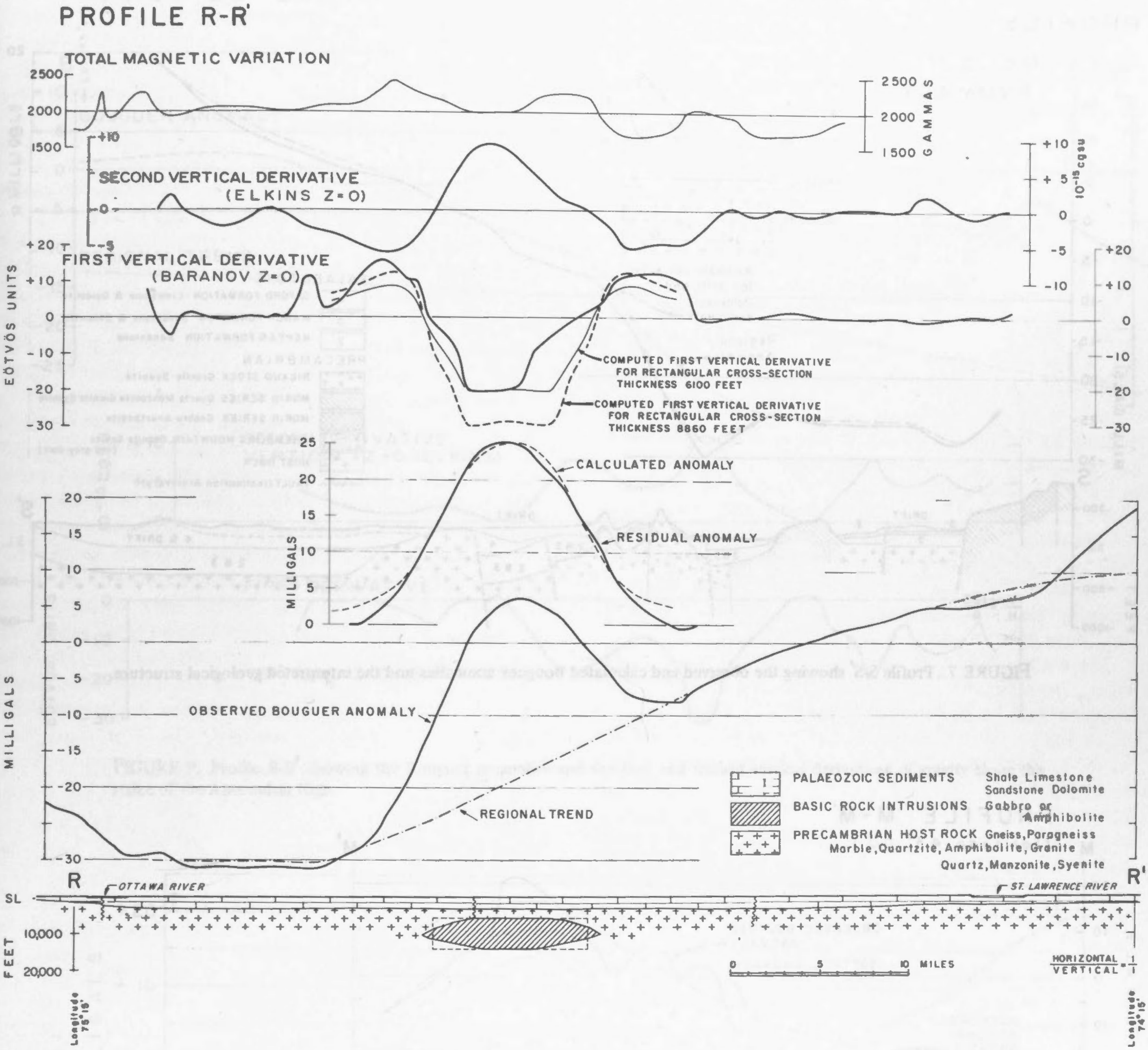

FIGURE 6. Profile R-R' showing the observed and calculated Bouguer anomalies, magnetic anomalies, first and second vertical derivative and the interpreted geological structure.

contrast with the host rocks is -0.06 gm/cm^3. Corrections for the effect of the drift and Paleozoic sediments were made to the Bouguer anomalies in profile S-S' (Figure 7).

One hundred feet of drift can cause a one-milligal change in the Bouguer anomaly. The corrections to this profile were based on the bedrock topography map obtained from seismic results (Hobson, 1962) and the geological map (Wilson, 1946).

A syenite body, rectangular in cross section, having a depth of 16,000 feet and a width of 20,000 feet with a density contrast of -0.06 gm/cm^3 explains the residual Bouguer anomaly low. A two-dimensional method (Hubbert, 1948) was used for the computations.

Plaisance Low. This Bouguer anomaly low of -36 mgal with a negative residual anomaly of 6.6 mgal (Figure 11) is probably related to the combined gravity effect of drift and a syenite intrusion similar to that of the Chatham-Grenville Stock and Mount Rigaud. Drift could account for all of the residual negative anomaly at the rate of 1 mgal per 100 feet. This would indicate a drift thickness of 660 feet which seems unlikely. Another alternative is to assume the negative anomaly is caused wholly by the syenite. A mass calculation was made on the residual anomaly obtained from six intersecting profiles taken across the Plaisance Low. The total mass deficiency was found to be 1.52×10^{11} tons. If the

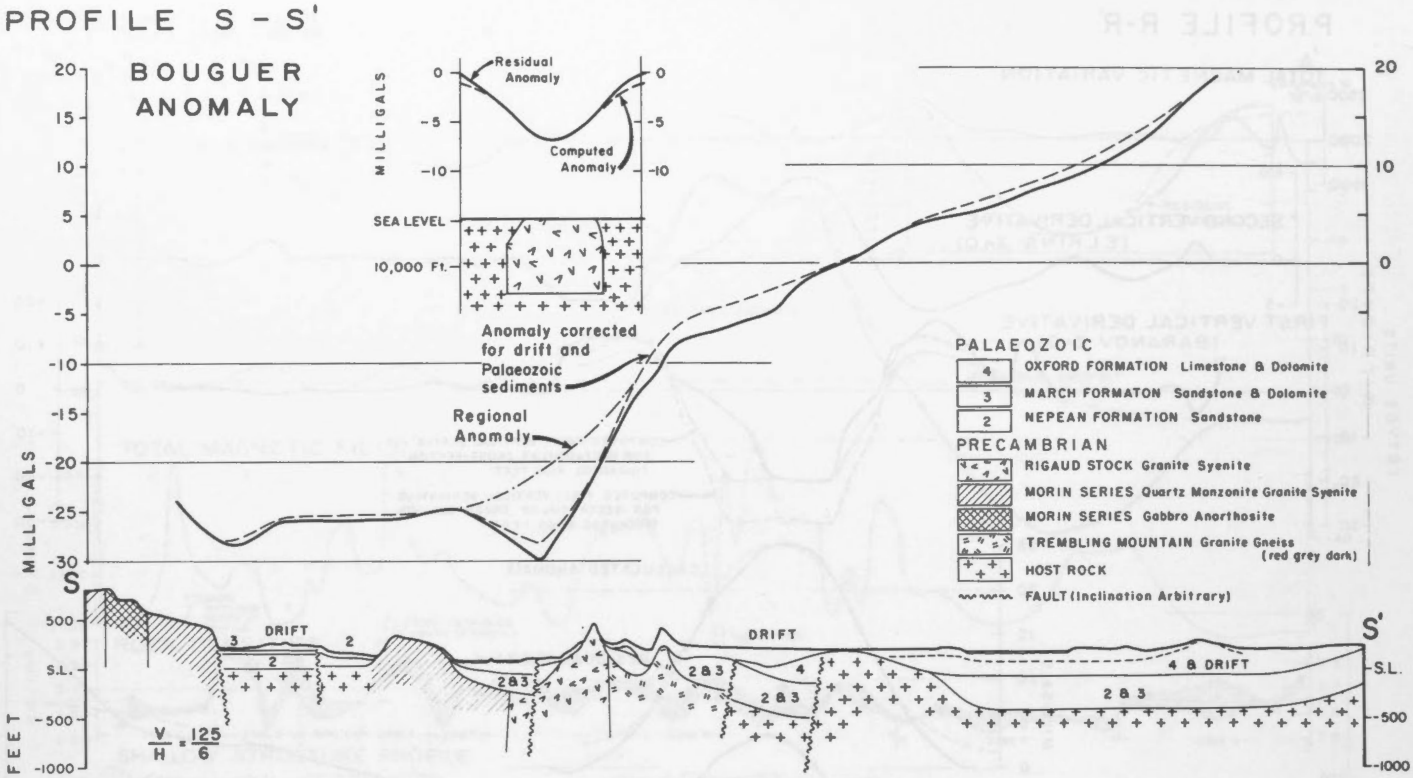

FIGURE 7. Profile S-S′ showing the observed and calculated Bouguer anomalies and the interpreted geological structure.

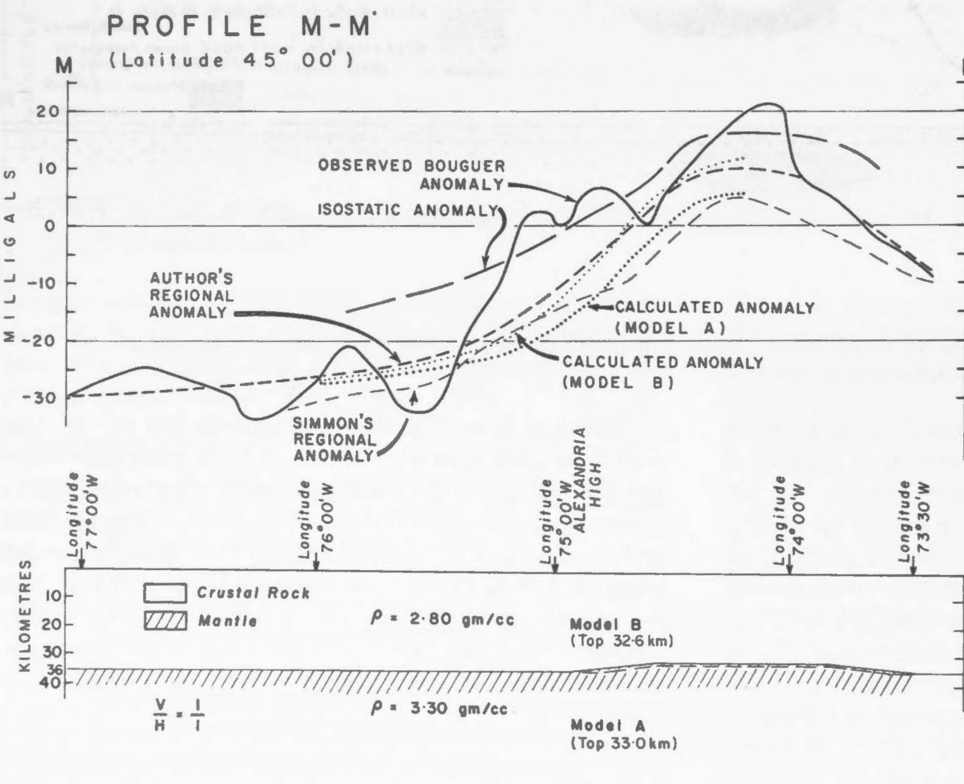

FIGURE 8. Profile M-M′ showing the observed and calculated anomalies and the crustal section along the Canadian-United States border.

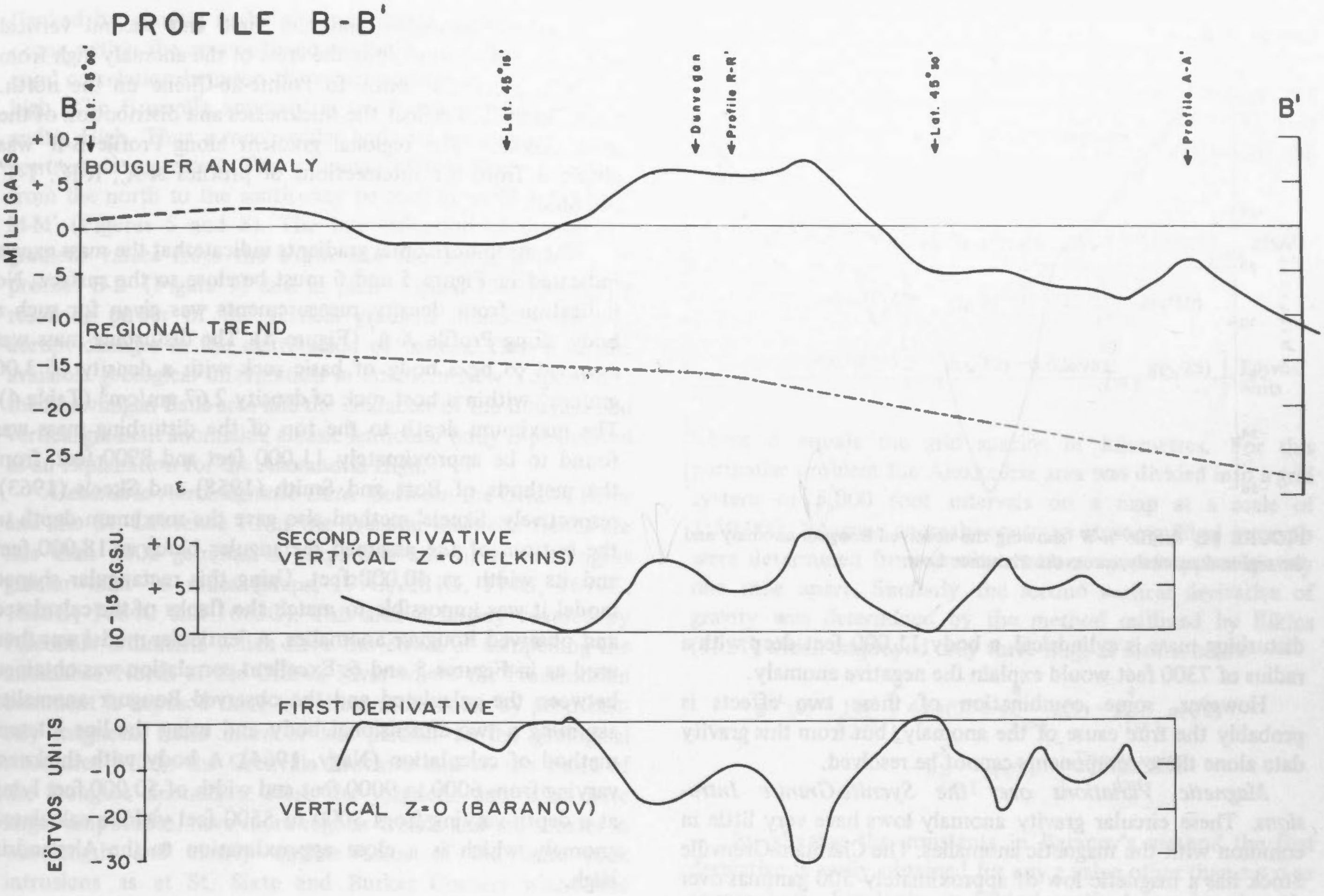

FIGURE 9. Profile B-B′ showing the Bouguer anomalies and the first and second vertical derivatives of gravity along the strike of the Alexandria High.

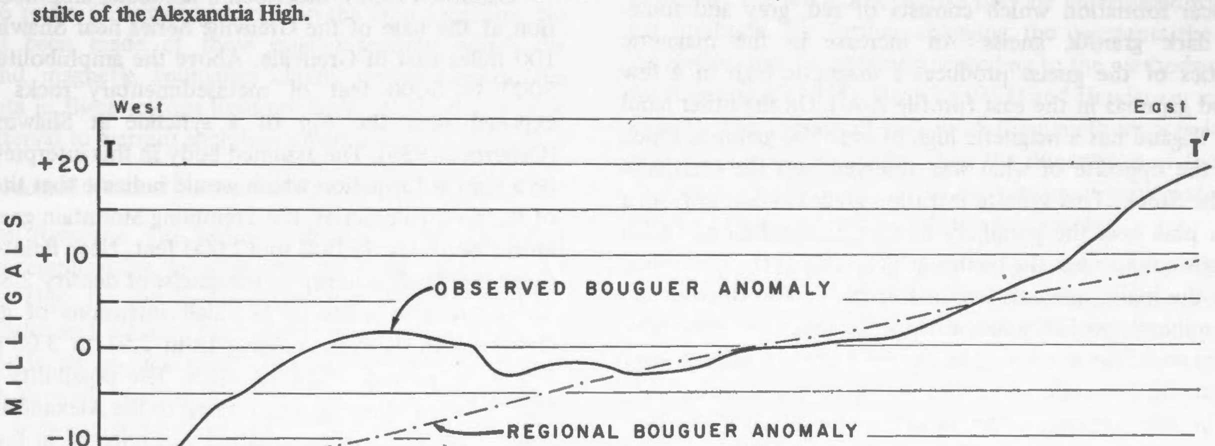

FIGURE 10. Profile T-T′ showing the observed Bouguer anomaly and the regional gradient.

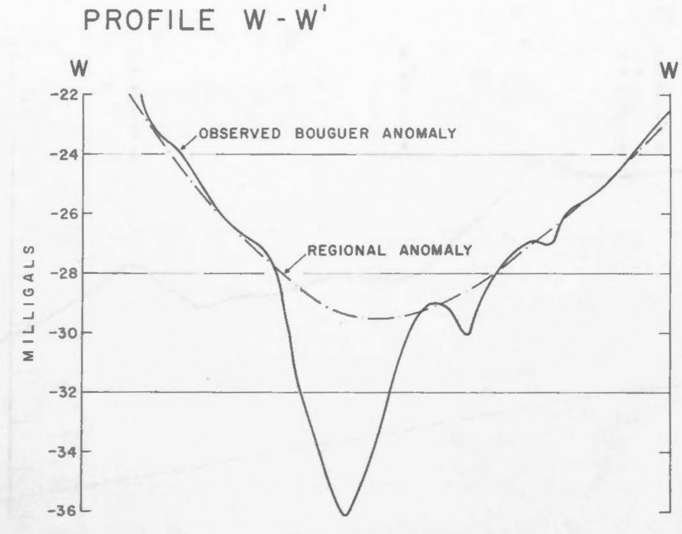

FIGURE 11. Profile W-W showing the observed Bouguer anomaly and the regional anomaly across the Plaisance Low.

disturbing mass is cylindrical, a body 11,000 feet deep with a radius of 7300 feet would explain the negative anomaly.

However, some combination of these two effects is probably the true cause of the anomaly, but from this gravity data alone these components cannot be resolved.

Magnetic Variations over the Syenite-Granite Intrusions. These circular gravity anomaly lows have very little in common with the magnetic anomalies. The Chatham-Grenville Stock has a magnetic low of approximately 500 gammas over the stock but then it is distorted on the easterly side by a geological formation which consists of red, grey and sometimes dark granitic gneiss. An increase in the magnetic properties of the gneiss produces a magnetic high of a few hundred gammas in the east (profile A-A′). On the other hand Mount Rigaud has a magnetic high of over 500 gammas which is just the opposite of what was observed over the Chatham-Grenville Stock. This syenite intrusion grades in colour from a reddish pink near the periphery to an amber colour and then to a dark colour near the centre, which reflects the dissemination of the mafic minerals within this body. This distribution of the minerals probably accounts for the magnetic anomalies. There is no obvious correlation between the Plaisance gravity low and the magnetic anomalies which have a northeasterly trend in this region. All three gravity lows have magnetic anomalies with different characteristics which indicate variations in the magnetic mineral content near the surface. These magnetic variations do not indicate corresponding density variations.

Alexandria High

Discussion. The Alexandria Bouguer anomaly high was divided graphically into regional and residual components (Figures 5, 6, 8, 9 and 10). The residual anomaly is about 16 miles wide over most of the map. In the south the anomaly is flatter and wider (Figure 8). Figure 9 shows the character of the residual anomalies and the first and second vertical derivatives of gravity along the crest of the anomaly high from Lunenburg on the south to Pointe-au-Chêne on the north. These anomalies reflect the thicknesses and distribution of the mass excesses. The regional gradient along Profile B-B′ was obtained from the intersections of profiles A-A′, R-R′, T-T′ and M-M′.

The steep horizontal gradients indicatethat the mass excess indicated in Figure 5 and 6 must be close to the surface. No indication from density measurements was given for such a body along Profile A-A′ (Figure 5). The disturbing mass was assumed to be a body of basic rock with a density of 3.00 gm/cm^3 within a host rock of density 2.67 gm/cm^3 (Table 4). The maximum depth to the top of the disturbing mass was found to be approximately 11,000 feet and 8900 feet, from the methods of Bott and Smith (1958) and Skeels (1963), respectively. Skeels' method also gave the maximum depth to the bottom of the assumed rectangular block as 18,000 feet and its width as 40,000 feet. Using this rectangular shaped model it was impossible to match the flanks of the calculated and observed Bouguer anomalies. A lenticular model was then used as in Figures 5 and 6. Excellent correlation was obtained between the calculated and the observed Bouguer anomalies assuming a two-dimensional body and using the line integral method of calculation (Nagy, 1964). A body with thickness varying from 6000 to 9000 feet and width of 50,000 feet lying at a depth varying from 3000 to 5500 feet yields a calculated anomaly which is a close approximation to the Alexandria High.

Osborne (1933), described a lenticular amphibolite formation at the base of the Grenville Series near Shawinigan Falls 100 miles east of Grenville. Above the amphibolite phase are 3000 to 5000 feet of metasedimentary rocks which are exposed near the top of a syncline at Shawinigan Falls (Osborne, 1936). The assumed body in this interpretation may be a similar formation which would indicate that the thickness of the Grenville Series, the Trembling Mountain gneiss and the Morin Series is 11,000 to 12,000 feet. Near Pointe-au-Chêne there is a small outcrop of paragneiss of density 2.85 gm/cm^3. There are also some local small intrusions of gabbro and diabase with densities ranging from 2.91 to 3.08 gm/cm^3 in the area of the Alexandria High. The possibility that these high-density rocks might be related to the Alexandria High was considered. But this explanation was rejected in favour of the first explanation because of the localized occurrence of these rocks and their associated magnetic anomalies.

To the south of the Alexandria area Simmons (1964) attributes the Grenville anomaly (the southerly continuation of the Alexandria High) to a density contrast between the Grenville Series and the adjacent surface rocks. Southeast of Ogdensburg where the Grenville anomaly crosses the Grenville Province, it is readily seen on the Geologic Map of New York (1961) that dense rocks such as paragneiss, amphibolite and gabbro predominate in the Grenville Series. These rocks are flanked by granitic rocks of lower density. The dense rocks occur within the area outlined by the high anomaly. There is good correlation between the structural trends and the gravity high. The Grenville anomaly is much wider than the Alexandria High. Thus a much wider body with a smaller density contrast is suggested. The widening of the Alexandria High from the north to the south may be seen in profiles A-A′ and M-M′ (Figures 5 and 8). The intensification of the vertical gradient values from the south and the north is shown in profiles B-B′ (Figure 9) and in plan (Figure 13). The higher resolving power of the vertical· gradient indicates areas of abrupt changes in the distribution of masses. Thus from the available geological information in northern New York and in the Shawinigan Falls area and the character of the Bouguer and vertical gradient anomalies, a basic lenticular body is postulated as an explanation for the Alexandria High.

Alexandria Aeromagnetic Data. Between the Ottawa River and the St. Lawrence River the irregular magnetic trends are less than 1000 gammas in amplitude and have wavelengths greater than 16 miles (Maps, 197G, 181G, 174G, 1677G, 1685G, 1684G and 1683G). This area is largely covered by Paleozoic sediments which have the effect of dampening the anomalies. North of the Ottawa River where the Precambrian basement is exposed there is a discernible north by northeasterly magnetic trend more or less parallel to the geological structures within the Grenville Province and to the trend of the Bouguer anomalies. Here the magnetic anomalies have larger amplitudes, have more regular trends and are shorter in wavelength and clearly outline some of the basic rock intrusions as at St. Sixte and Burkes Corners where the residual anomaly high is over 3000 gammas and the wavelength is 6 miles. Gravity highs exist in the same localities. No study has been made of these smaller features which the gravity and magnetic anomalies clearly define because the gravity data in these regions have not been collected at a close enough interval to warrant such investigations.

First and Second Vertical Derivatives of Gravity

General Remarks. The higher vertical derivatives are best suited for emphasizing local gravity anomalies such as the Alexandria High for the simple reason that they suppress the constant fields and enhance the variable or anomalous portions of the fields which are related to surface or near-surface masses. In general, positive and negative values of the second derivative indicate areas of mass excess and mass deficiency respectively, whereas values of the first derivative indicate the same relations but with a reversal of sign. A further advantage of using these derivatives is that they have a greater resolving power, thus neighbouring perturbing bodies can be delineated even though in the Bouguer anomaly field only one single anomaly is apparent. A good example of this has been reported by Elkins (1951) for the Mykawa gravity low in the Texas Gulf Coast area. The residual gravity low indicated only one large mass deficiency but the second derivative indicated four separate minima which correspond to four salt domes. Various methods of determining the first and second derivative have been discussed by many authors and have been reviewed by Grosse (1957), and Danes and Oncley (1962).

In this report the first vertical derivative of gravity was determined by the method outlined by Baranov (1953). This method for a six-ring case was programmed employing the following formula:

$$g^1(0) = \frac{10}{S}\Big[-2.30518\,g(0) + 0.42744\sum_{i=1}^{4} g(1) + 0.01321\sum_{i=1}^{4} g(\sqrt{2}) + 0.02175\sum_{i=1}^{8} g(\sqrt{5}) + 0.01197\sum_{i=1}^{8} g(\sqrt{10}) + 0.04972\sum_{i=1}^{12} g(\sqrt{17}) - 0.02698\sum_{i=1}^{12} g(\sqrt{25})\Big] \text{ Eötvös units}$$

where S equals the grid spacing in kilometres. For this particular problem the Alexandria area was divided into a grid system of 5,000 foot intervals on a map at a scale of 1:50,000. Bouguer anomaly contours at one-milligal intervals were determined from gravity stations spaced approximately one mile apart. Similarly the second vertical derivative of gravity was determined by the method outlined by Elkins (1951) which employed only three rings as shown below:

$$g^{11}(0) = \frac{100}{62S^2}\Big[44\,g(0) + 4\sum_{i=1}^{4} g(1) - 3\sum_{i=1}^{4} g(\sqrt{2}) - 6\sum_{i=1}^{8} g(\sqrt{5})\Big] \frac{\text{Eötvös units}}{\text{km}}$$

By altering the constants in Baranov's method the first derivative is easily obtained for any z value other than $z = o$ as shown here. Similarily in Elkins' method by changing the constants the second derivative may be determined for any of his methods. By further changing the constants the second derivative may be obtained according to the methods outlined by Rosenback (1953), Haalck (1953) and Henderson and Zietz (1949). The important fact in all these methods is to keep the grid spacing much smaller than the dimensions of the bodies that are to be defined and to use measured gravity stations at intervals more or less equal to the grid spacing.

Results. The vertical gradient on the plane $z = o$ (Figure 12) has minimum values of −39 Eötvös units over the crest of the Beauharnois anticline, −36 Eötvös units near the peak of the Alexandria High, and peak values of +51 Eötvös units over the Plaisance gravity low and +34 Eötvös units over the southern part of the Chatham– Grenville Stock. Generally, the negative zones of the vertical gradient indicate mass excesses and the positive areas indicate mass deficiencies. For example, the zone of negative gradient values striking northeasterly parallel to the Alexandria High indicates a mass excess, and a positive zone over the Plaisance Low indicates a mass deficiency. The easterly and westerly limits of the zero contours of the negative zone, which goes from the north to the south near the centre of the map area, show the lateral variation of the outer limits of the previously postulated basic lenticular body. The negative contours within this boundary indicate the isopycnic contours of the mass excess.

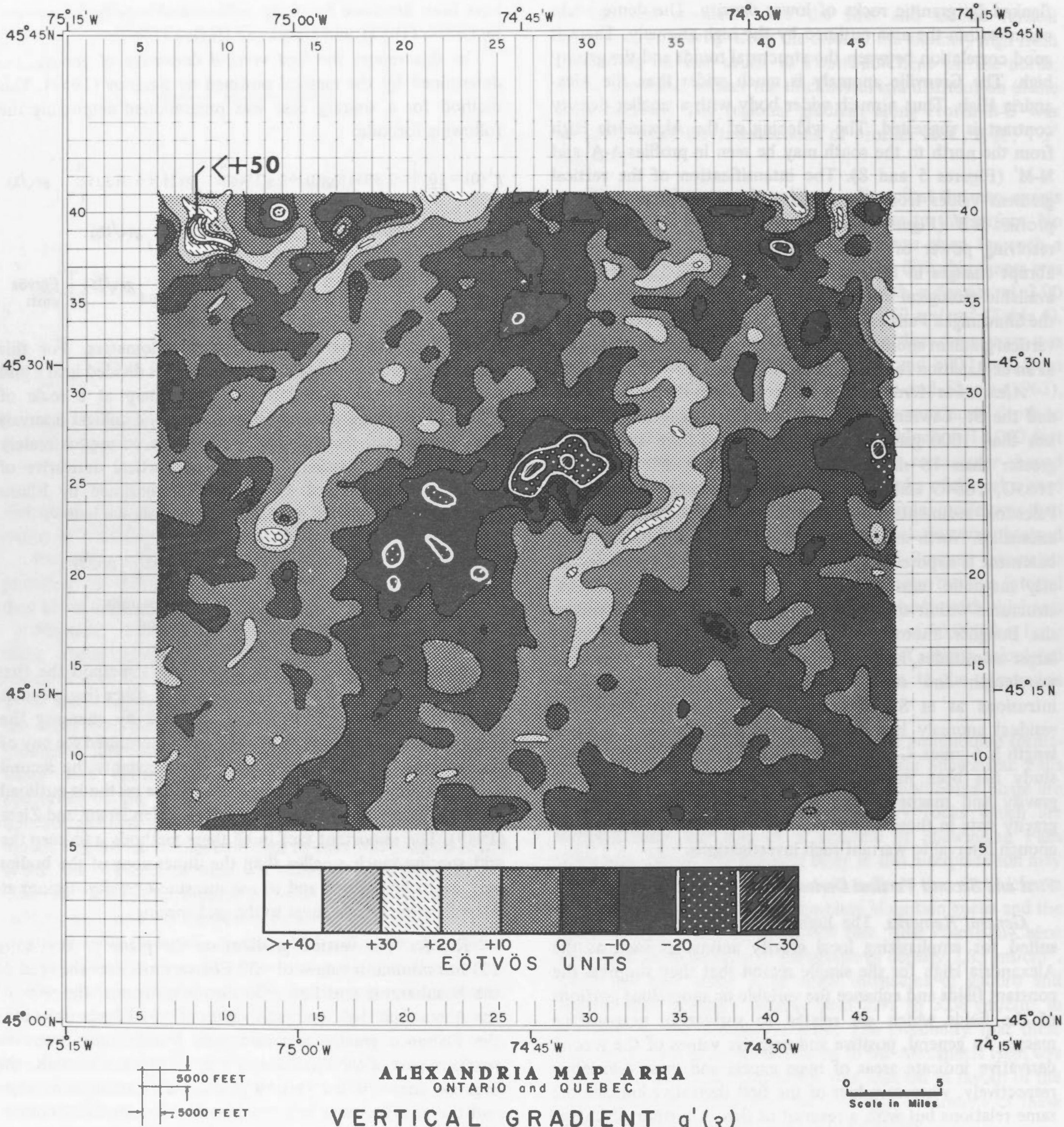

FIGURE 12. Vertical gradient of gravity by Baranov's method on the plane $z = 0$.

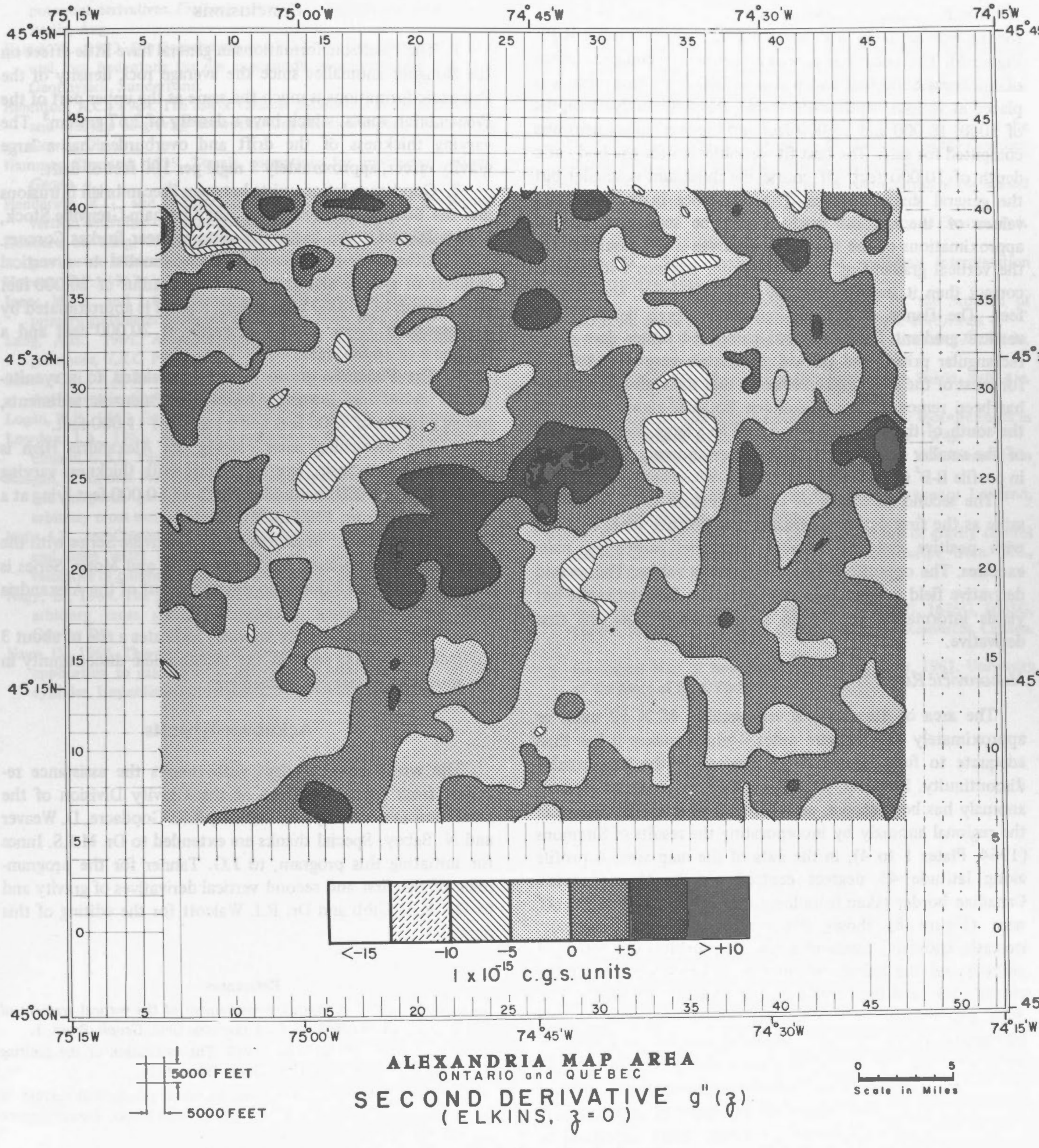

FIGURE 13. Second vertical derivative of gravity by Elkins' method on the plane $z = 0$.

A curve-fitting method for the vertical gradient was tried for the existing body with some minor changes (Profile R-R′, Figure 6). The body was approximated to a rectangular prism of thickness 8800 feet and width 45,000 feet. This prism was placed at various depths with the centre of the body at depths of 5000, 10,000 and 15,000 feet and the vertical gradient was computed for each. The best fit was obtained for the body at a depth of 10,000 feet. Of course the minimum is smaller but the general shape matches. The difference in the minimum values of the vertical gradient can be explained by the approximations of the two methods. Even if it is assumed that the vertical gradient as computed from Baranov's method is correct then it suggests that the body is thinner, about 6100 feet. The flanks of the minima would agree better if the vertical gradient for a lens was computed rather than for a rectangular prism. The vertical gradient is very close to zero for most of the area, which indicates that the regional anomaly has been removed. The Alexandria Bouguer anomaly high to the south of the map area is removed to a large degree because of the smaller variation of the Bouguer anomaly. This is seen in profile B-B′ (Figure 9).

The second derivative of gravity (Figure 13) is much the same as the first derivative except that positive areas coincide with positive residual Bouguer anomalies indicating mass excesses. The opposite is true for negative values. The second derivative field is much smoother than the first derivative but yields information similiar to that obtained from the first derivative.

Mohorovičić Rise

The area of discussion is very small – 48 × 52 miles or approximately 2500 square miles – which makes it less than adequate to fully discuss either isostasy or the Mohorovičić discontinuity. However, since in most of the profiles a regional anomaly has been shown, an effort has been made to explain the regional anomaly by incorporating the results of Simmons (1964, Plates 1 to 4), in the data of the map area. A profile along latitude 45 degrees centred on the United States-Canadian border taken from longitude 73° 15′ west to 77° 00′ west (Figure 8) shows the observed Bouguer anomaly, isostatic anomaly, assumed regional anomaly (Simmons and author) and the calculated anomaly. If the densities of the crustal rocks and the mantle rocks are assumed to be 2.80 and 3.30 gm/cm^3, respectively, then an uplift of 3 to 3.3 kilometres from the assumed general level of −36 kilometres will explain the regional anomaly from −30 to +5 mgal (Simmons) or +10 mgal (author). Similarily the regional anomalies in the other profiles are explained by undulations in the Mohorovičić discontinuity. A similar result was found by Simmons who states, "The regional picture can be explained on the basis of two ridges in the Mohorovičić discontinuity, one trending north-south situated beneath the mountains, the other east-west and centred on the Canadian border."

Another possibility may be a variation in density of the crustal column by .02 gm/cm^3, which could also account for the regional anomalies.

Conclusions

1. The Paleozoic formations in general have little effect on the Bouguer anomalies since the average rock density of the Paleozoic formations is much the same as the upper part of the Precambrian rocks, which have a density of 2.67 gm/cm^3. The varying thickness of the drift and overburden has a large gravity effect, approximately 1 mgal per 100 feet of drift.

2. Good correlation exists between Precambrian intrusions and the Bouguer anomalies, e.g., the Chatham-Grenville Stock, Mount Rigaud and a basic rock outcrop near Burkes Corners. The Chatham-Grenville Stock is approximated to a vertical cylinder of syenite and granite having a radius of 20,000 feet and a length of 37,000 feet. Mount Rigaud is approximated by a rectangular block having a width of 20,000 feet and a thickness of 16,000 feet.

3. The Plaisance gravity low is correlated to a syenite-granite cylindrical intrusion below the Paleozoic sediments, having a radius of 7300 feet and a length of 11,000 feet.

4. The disturbing mass causing the Alexandria High is interpreted as a basic, lenticular body with thickness varying from 6000 to 9000 feet and a width of 50,000 feet lying at a depth varying from 3000 to 5500 feet.

5. The probable thickness of the Grenville Series with the intrusions of Trembling Mountain gneiss and Morin Series is about 11,000 to 12,000 feet along the crest of the Alexandria High.

6. The regional gravity anomaly indicates a rise of about 3 kilometres (10,000 feet) in the Mohorovičić discontinuity in the southeast corner of the map area.

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