GRAVITY MAP SERIES

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Results of Regional Underwater Gravity Surveys in the Gulf of St. Lawrence with map

No. 86 - Gulf of St. Lawrence

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B. G. Brule
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CANADA

Department of Energy, Mines and Resources
OBSERVATORIES BRANCH
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CONTENTS

RESULTS OF REGIONAL UNDERWATER GRAVITY SURVEYS IN THE GULF OF ST. LAWRENCE

A. K. Goodacre, B. G. Brule and R. V. Cooper

ABSTRACT - The Dominion Observatory regional underwater gravity survey of the Gulf of St. Lawrence was continued in 1966 and 1967. Some 1,200 gravity stations have now been established in the Gulf during the period 1962-1967. Equipment and survey techniques used in the survey are described and the method of reduction of the underwater gravity results is reviewed.

The Bouguer anomaly field over the norther portion of the Gulf of St. Lawrence is similar to that of the adjacent Precambrian Shield. A distinct change in anomaly level from negative in the north to more positive in the south occurs in the Gulf and is believed to mark the boundary between the Grenville and Appalachian geological provinces. Basic intrusive rocks characteristic of the boundary between these provinces are outlined by a belt of positive anomalies from Gaspé Peninsula to Port-au-Port Peninsula, Newfoundland. A gravity minimum of -60 mgal near Magdalen Islands has been attributed to abnormally light Carboniferous sediments or Devonian granitic rocks or alternatively their combined effect. The gravity anomalies between southwestern Newfoundland and Cape Breton Island suggest a structural continuity between these areas.

RÉSUMÉ - La Direction des observatoires a poursuivi en 1966 et en 1967 son programme régional de levés gravimétriques sous-marins dans le golfe Saint-Laurent. Les scientifiques ont établi environ 1,200 stations gravimétriques dans le golfe au cours de la période de 1962 à 1967. L'auteur décrit les instruments et les techniques utilisés et présente la méthode de réduction des résultats gravimétriques sous-marins.

Le champ des anomalies de Bouguer qui couvre la partie septentrionale du golfe Saint-Laurent est semblable à celui du Bouclier précambrien adjacent. Un changement marqué dans l'intensité des anomalies, de négatives au nord à plus positives au sud, se présente dans le golfe et marque, croit-on, la frontière entre les provinces géologiques de Grenville et des Appalaches. Les roches intrusives basiques qui caractérisent la frontière entre ces deux provinces sont délimitées par une zone d'anomalies positives s'étendant de la péninsule de Gaspé à celle de Port-au-Port (Terre-Neuve). Un minimum de -60 mgal à proximité des îles de la Madeleine a été attribué aux sédiments carbonifères anormalement légers ou à des roches granitiques du Dévonien ou encore à leurs effets conjugués. Les anomalies de gravité entre la partie sud-ouest de Terre-Neuve et l'île du Cap-Breton semblent indiquer une continuité structurale entre ces deux régions.

INTRODUCTION

Field parties from the Dominion Observatory made regional underwater gravity surveys in the Gulf of St. Lawrence during 1962, 1963, 1966 and 1967 (Figure 1) and obtained a total of 1200 readings distributed at intervals of approximately 8 miles. The results of the work done in 1962 and 1963 in the southern part of the Gulf, and a structural interpretation of the major gravitational features have been presented previously (Goodacre, 1964a; Goodacre and Nyland, 1966). This report presents the results of the surveys that were carried out in the central and northern portions of the Gulf in 1966 and 1967. In addition, a description of the equipment and survey techniques, and a brief review of the methods of reducing the underwater gravity measurements are given.

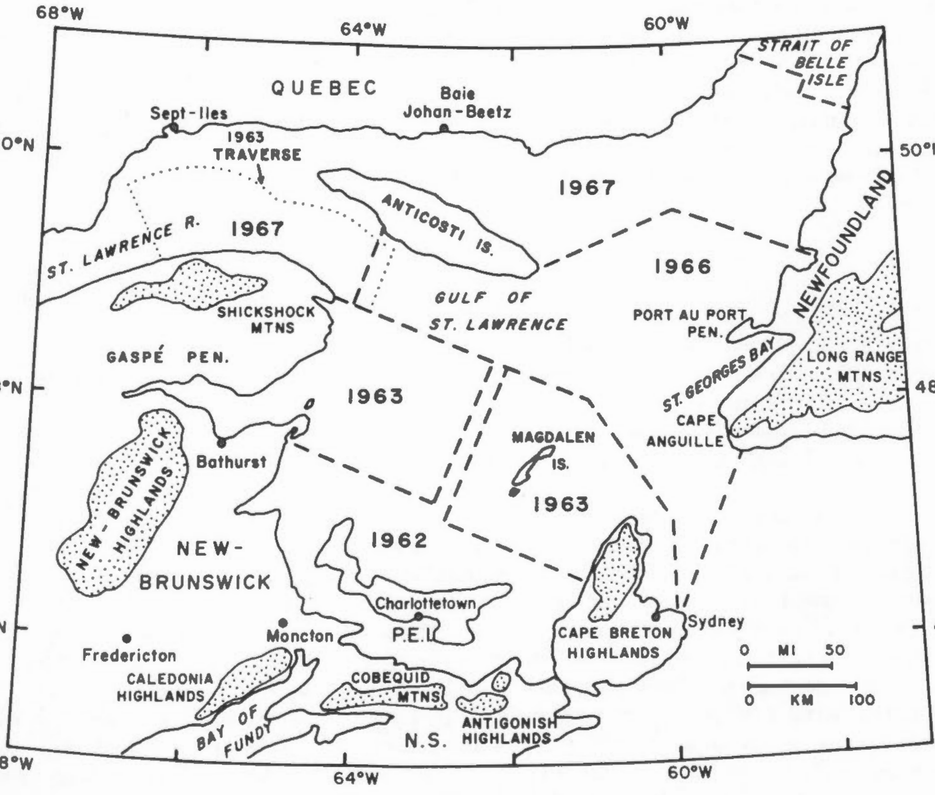

Figure 1. Location map showing areas covered yearly by underwater gravity surveys.

GULF OF ST. LAWRENCE CRUISE INFORMATION

General Location of Measurements	Vicinity of Prince Edward Island	West Central portion of Gulf of St. Lawrence	Vicinity of Magdalen Is.	Between Gaspé Peninsula and SW coast of Newfoundland	Northern portion of Gulf of St. Lawrence from Saguenay R. to St. of Belle Isle
Ship	MV North Star VI	MV Theta	MV Theta	CNAV Sackville	CNAV Sackville
Cruise Dates	Aug. 15 to Aug. 25, 1962	July 11 to July 22, 1963	Aug. 22 to Sept. 4, 1963	May 30 to June 30, 1966	May 29 to June 30, 1967
Number of Days at Sea	9	10	10	25	27
Gravity Observers	E. Derenyi A.K. Goodacre E. Nyland	A.K. Goodacre J. Steiner H.D. Valliant	A.K. Goodacre J. Steiner P.J. Winter	B.G. Brule R. Mason L. Strawczynski	R.V. Cooper A.K. Goodacre J.D. Panar
No. of Underwater Gravity Observations	157	188	131	326	398
Approx. Drift Rates of LaCoste and Romberg Gravimeters	H2G: no long-term drift	H2G: less than +3 mgal/month	H2G: +0.2 mgal/day adopted between 791663 and 799763	H2G: +1 mgal/month at operating temperature 53°C	H2G: less than +1 mgal/month G25A: no long-term drift
Gravity Control Stations	9801/62 Pictou, N.S.	9402/62 Ste Anne des Monts, Que. 940363 Grande Rivière, Que.	9892/62 North Sydney, N.S.	9861/62 Dartmouth, N.S. 989462 Sydney, N.S. 920164 Corner Brook, Nfld.*	9861/62 Dartmouth, N.S. 989462 Sydney, N.S.
Detail Station Sequence	8001/62 to 8158/62	7707/63 to 7887/63	7901/63 to 8036/63**	5002/66 to 5314/66	6010/67 to 6400/67***
Decca Chain(s)	7 and 9	9	9	6 and 9	6 and 9

*Discontinuities in gravimeter readings occurred due to changes in operating temperature of H2G. **Readings at stations 7932/62 to 7943/63 and at station 7998/63 were discarded due to a malfunction of the gravimeter. ***Stations 6180/67 and 6377/67 were discarded due to suspected errors in gravity readings.

A Bouguer anomaly map, included with this report, combines the results* of all the underwater surveys and has been compiled at a scale of 1:1,000,000 for comparison with a series of geological and bathymetric maps which are being prepared on the same projection and scale by the Department of Energy, Mines and Resources.

THE UNDERWATER GRAVITY SURVEYS

General Information

The history of the regional underwater gravity surveys of the Gulf of St. Lawrence is given in the accompanying table. Transportation for the underwater gravity surveys was provided by the Bedford Institute of the Marine Sciences Branch, Department of Energy, Mines and Resources. Each of the three ships used was approximately 200 feet long and was equipped with an echo sounder, a radar set and a Decca Navigator receiver. The underwater gravimeter and associated equipment consisting of a cable, block, hydraulic winch and diesel pumping unit were installed for the duration of a cruise. Altogether 102 days of ship time were used in the surveys from 1962 to 1967; 81 days were spent at sea and the remaining 21 days in maintaining the gravimeters and associated equipment and reading the gravimeters at land gravity control stations during fuelling and provisioning of the ships. Twelve hundred gravity observations were made during the 81 days at sea for an average value of 15 gravity observations per day at sea.

The Underwater Gravimeters and Associated Equipment

The underwater gravimeters, manufactured by LaCoste and Romberg of Austin, Texas, U.S.A., are essentially land-gravimeter units suspended in gimbals and enclosed in a watertight case (Figure 2). After lowering to the sea floor, the instruments are levelled automatically and operated by means of a remote-control unit in the ship. A reliable connection between the underwater gravimeter and the control unit is essential. This is provided by a multiwire cable which connects the gravimeter and control box and supports the instrument while being lowered to and raised from the sea floor.

During the 1962 and 1963 surveys a 1 1/4-inch diameter, 1200-foot-long, neoprene-covered, 48-conductor cable, manufactured by Vector Cable Co. of Houston, Texas, U.S.A., was employed. This cable proved to be unsatisfactory as on several occasions the neoprene jacket was cut by sharp rocks on the sea floor which permitted flooding and short-circuiting of the conductors in the lower end of the cable. This cable was replaced in 1964 with a more durable 13-wire armoured cable (5/8 inch diameter) manufactured by the Vector Cable Co. (Figure 3), and was used during the 1966 and 1967 surveys. The gravimeters had to be modified for operation with 13 wires instead of 48 wires and a special (Figure 4) block constructed of sufficient diameter (40 inches) to accommodate the bending radius (18 inches) of the new cable. The

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*Computer listings of the principal facts for the gravity stations on the accompanying map may be obtained on request from the Gravity Division of the Dominion Observatory, Ottawa.

Figure 2. LaCoste and Romberg underwater gravimeter.

armoured cable has proved to be quite satisfactory; a minor difficulty is that the gravimeter end of the cable becomes kinked and corroded with normal use so that approximately 150 feet of cable must be removed after each field season.

Three hydraulic winches, constructed by J. Swann Ltd. of Vancouver, B.C., have been employed by the Dominion Observatory for underwater surveys. The winches are designed to provide smooth positive control in both forward and reverse directions and to facilitate safe handling of the gravimeters at all times. Another important function of the winches is to provide a continuous reliable connection between the underwater gravimeter and its control unit. Winch No. 1, used only for the early underwater surveys, did not employ slip-rings for this function as it was thought they might not be reliable enough to conduct several weak output voltages from the gravimeter using the 48-conductor cable. Instead, a small drum for the control-box cable was mounted on the shaft supporting the large storage drum for the gravimeter cable and a permanent connection between the two cables was made through the shaft. When the winch is in

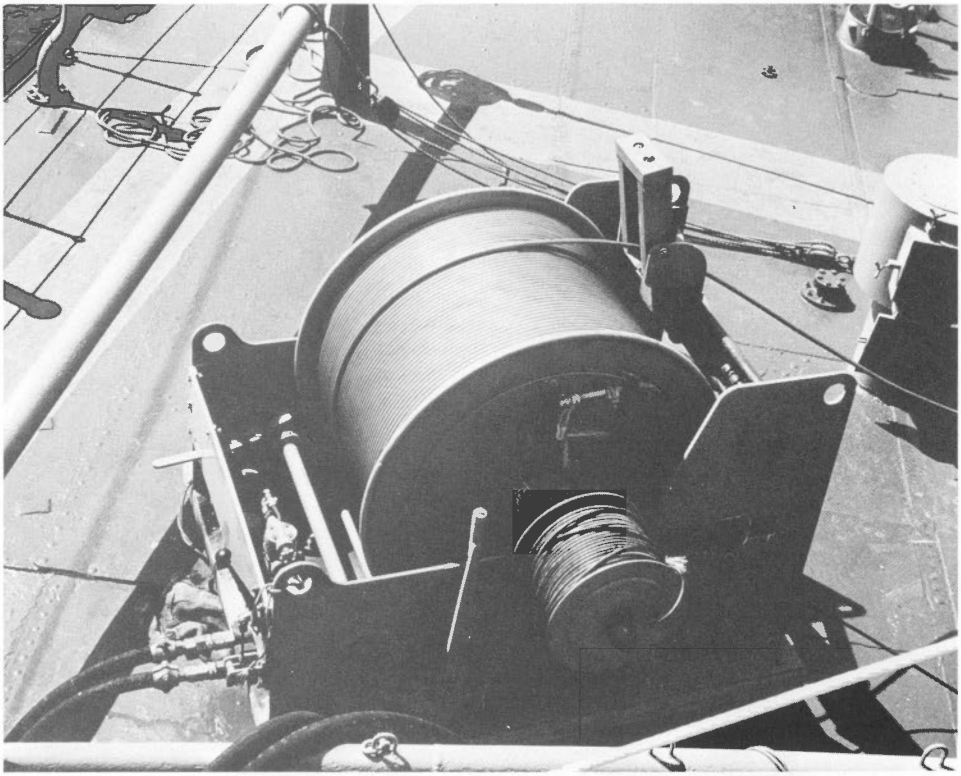

Figure 3. Swann hydraulic winch wound with Vector armoured cable.

operation, the smaller cable unwinds onto the deck while the gravimeter is being lowered to the ocean floor.

The other two winches, No. 2 and 3, are similar to No. 1 winch but are designed to store up to 3500 feet of armoured cable and are equipped with automatic spooling devices (Figure 3). In addition, these winches are provided with slip-rings as the 13-wire version of the LaCoste and Romberg gravimeter provides relatively high-voltage electrical signals. So far no difficulty has been encountered in using the slip-rings as long as salt water is kept out of the electrical connectors of the winch.

The only serious problem affecting the gravimeter readings during the course of the survey resulted from the malfunction of the mercury thermostat in the heater circuit used to maintain the gravimeter at a constant temperature. Severe impulses tended to separate the mercury in the capillary of the thermostat resulting in a change in the operating temperature of the instrument. This produced discontinuities in the gravity readings that could only be recognized with certainty by repeating measurements at sea or at land gravity control stations. Such discontinuities from this cause

Figure 4. Underwater gravimeter being taken in after a reading.

were particularly frequent during the 1966 survey. To overcome this difficulty the mercury thermostat in each gravimeter was replaced with thermistors which virtually eliminated all problems of temperature control. When operating at constant temperature, the LaCoste and Romberg underwater gravimeters generally exhibited drift rates of less than 1 mgal/month (see table) and it was possible to repeat a gravity measurement to within ± 0.3 mgal.

Survey Procedure

In planning each day's survey the approximate Decca positions of the gravity stations to be measured usually are given a day or two in advance to the ship's navigation officer who plots the positions on his navigation chart. In carrying out the survey the officer on watch guides the ship to the positions indicated on the chart. When the ship is on station, the underwater gravimeter is lowered to the sea floor, read, raised and brought back on deck (Figure 4). Decca coordinates and the water depth are recorded while the instrument is on the sea floor. About 15 minutes are usually required to position the ship and to lower, level, read and raise the gravimeter. Approximately 40 to 50 minutes are needed to travel between the stations which are spaced about 8 miles apart; in good weather, about one gravity station can be established each hour.

The main problem in obtaining an underwater gravimeter reading is to keep the ship from drifting excessively and dragging the instrument on the sea floor while trying to maintain station. Once the ship is in position with either the bow or stern headed into the wind and waves, and with an engine running at a slow speed, the ship's officer keeps the ship on station by continuously noting the attitude of the gravimeter cable with respect to the ship and by maneuvering accordingly. The ship is always positioned so that any drift is away from the gravimeter to avoid fouling the multi-conductor cable on the ship's keel or propeller. Little trouble is experienced in using the gravimeter in deep water as the sea floor was generally muddy or sandy and as the pull on the instrument is nearly vertical when being brought to the surface. On the other hand, the consequences of letting the ship drift while operating in shallow water are often more serious as the gravimeter must be dragged almost horizontally over the sea floor while being reeled in. On one occasion while operating in shallow water during the course of these surveys the instrument suffered damage on the rocky sea floor which resulted in a change in its operating temperature with a corresponding discontinuity in its drift rate.

Horizontal Positions and Depth Measurements

The latitude and longitude for each gravity station were obtained by scaling the Decca readings on standard hydrographic charts printed with Decca lattice overlays. The problems of obtaining accurate geographical coordinates from Decca positions and of measuring precisely the depth of water have been described previously (Goodacre, 1964b); only certain points will be reviewed here. The magnitude of the systematic differences between the latitude and longitude calculated from the Decca readings and the accepted geographical coordinates for a point depends on the geometry of the locations of the Decca receiver and transmitters and the intervening land and water transmission paths. Systematic errors in the Decca pattern usually are taken into account but sufficient information is not yet available for the open-water portions of the Gulf of St. Lawrence to enable corrections to be made. However, on the basis of comparisons of radar positions and Decca positions, and geographical coordinates obtained from different Decca chains for the same position, it is unlikely that systematic errors exceed 1/2 mile in most parts of the Gulf of St. Lawrence. Random errors in the Decca readings are caused mainly by interference of the ground and sky waves at night and tend to be more pronounced the farthur away the receiver is from the transmitters. These errors are probably less than $\pm 1/4$ mile in most areas, with the largest errors in the remote, northeastern part of the Gulf of St. Lawrence. The effect of random errors can be minimized by taking repeated Decca readings while a gravity measurement is made but in most cases this is not done as the officer on watch is busy keeping the ship on station.

Accurate water depths are difficult to obtain during underwater gravity surveys. The biggest problem is to ascertain how the depth sounder provided with the ship has been calibrated. Some sounders are adjusted to read the depth of water below the keel while others give the depth below the surface of the water. In addition, some sounders may be adjusted for a speed of sound that is not representative of the value for the area in which the survey is carried cut. Calibrations of the echo sounders were made whenever possible, and the revised depths used in the reduction of the gravity data. However the water depths obtained during the surveys have not been corrected for the effect of marine tides which may be as high as 10 feet but are generally less than 5 feet. It is estimated that a systematic error of as much as 20 feet may be present in some of the depth measurements in the Gulf of St. Lawrence and that random errors in the water depths seldom exceed ± 10 feet.

Depth gauges using potentiometer-type pressure transducers were installed in the gravimeters by LaCoste and Romberg in 1966 and used during the 1966 and 1967 surveys. They are considered to be capable of measuring depths with a precision of better than 1%. While they seemed to work well, their performance is still under investigation.

REDUCTION OF THE GRAVITY OBSERVATIONS AND ESTIMATION OF ERRORS IN THE BOUGUER ANOMALIES

The underwater gravity results, presented as simple Bouguer anomalies, are directly comparable to the gravity data available for the land areas surrounding the Gulf of St. Lawrence (Garland, 1953; Tanner and Uffen, 1960; Weaver, 1967). To reduce the underwater observations to a common elevation datum, the observed gravity readings were extrapolated to the surface of the sea taking into account the normal free air vertical gradient of gravity and the attraction of the layer of water above the instrument, according to the following relation:

$$\begin{aligned} g_s &= g_{obs}(1 - 2d/R) + 4\pi\gamma\rho d \\ &= (g_{obs} - 0.068\ d)\ \text{mgal} \end{aligned} \qquad (1)$$

where g_s is the gravity at the surface, g_{obs} is the observed gravity, R is the radius of the earth, γ is the gravitational constant, ρ is the density of sea water (1.03 g/cm^3), and d is the observed depth in feet.

Bouguer anomalies were calculated in the usual way by adding to the surface gravity value a correction of 0.021 d mgal for the mass deficiency of water with respect to rock of standard density 2.67 g/cm^3 and subtracting a theoretical gravity value (g_{th}) at the station computed from the International Gravity Formula of 1930. The Bouguer Anomaly is given by

$$\Delta g\ (\text{Bouguer}) = (g_{obs} - 0.047\ d - g_{th})\ \text{mgal} \qquad (2)$$

In areas of rugged underwater topography the approximation of the topographical variations by a plane surface is not adequate and a terrain correction must be applied to the 'simple' Bouguer anomaly to form the 'complete' Bouguer anomaly. No detailed study of the magnitude of the terrain correction, which is always positive, has been made for the underwater gravity stations in the Gulf of St. Lawrence. However it has been estimated to be about 1 mgal for stations in the deep trough between Anticosti Island and the Gaspé Peninsula and to be negligible for most stations on the remaining relatively featureless floor of the Gulf.

Based on experience on the Shipborne Gravimeter Testing Range near Halifax, N.S. (Goodacre, 1964b), the error in the adopted vertical gradient due to anomalous mass distributions is probably less than 1% in most cases. The equivalent error in g_s is less than 1 mgal if the water depth is under 1000 feet. A correction for marine tide (Bott, 1961) was not applied; the maximum error in neglecting this correction is around 1/2 mgal for most areas of the Gulf of St. Lawrence.

The simple Bouguer anomaly at an underwater station may be subject to both systematic and random errors in observed gravity, observed depth, navigation and adopted vertical gradient as well as the error in neglecting the marine tide correction. The maximum systematic errors in the Gulf of St. Lawrence for these parameters are as follows: observed gravity 1/2 mgal, observed depth 20 feet, geographical position 1 mile, vertical gradient of gravity 0.001 mgal/ft, lack of marine tide correction 1 mgal. Therefore, a systematic error of up to 2 or 3 mgal could be present in the Bouguer anomalies, particularly in those areas of the Gulf which are either very deep or far away from Decca transmitter sites. However the anomalies should exhibit little systematic error elsewhere. Systematic errors in the Bouguer anomaly values will have to be taken into account if the regional underwater measurements are used to supplement detailed underwater gravity surveys or to control surface gravimeter measurements.

The estimates quoted in the previous section for the random errors in the observed gravity values ($\pm$0.3 mgal), depth values ($\pm$10 feet), and in the positions ($\pm$1/4 mile), have been obtained from the data presented in the Appendix. Sections A, B, C and D of the Appendix give the locations, water depths, observed gravity values and Bouguer anomalies for underwater gravity stations reoccupied in the Gulf of St. Lawrence in the same year and sections E and F give data for stations reoccupied in different years. To obtain an estimate of the random error in a simple Bouguer anomaly value, a histogram of the differences between the observed anomalies and the mean values for reoccupied stations versus the number of cases is presented in Figure 5 using the anomalies given in the Appendix.

Because of difficulties with the gravimeter, most of the 1966 data and some of the 1963 data were adjusted using repeated measurements and therefore the readings marked with an asterisk in Section B and all the readings in Section C have been omitted from the histogram in Figure 5. It can be seen readily from the histogram that most of the Bouguer anomalies at reoccupied stations are within 1 mgal of the mean values. If all of the anomalies in the Appendix are considered, the majority of the Bouguer anomalies are within 1 1/2 mgal of the mean values at reoccupied stations. It is concluded therefore that the underwater gravity surveys provide data that are self-consistent and are comparable in quality to those obtained in regional surveys on land (Weaver, 1967).

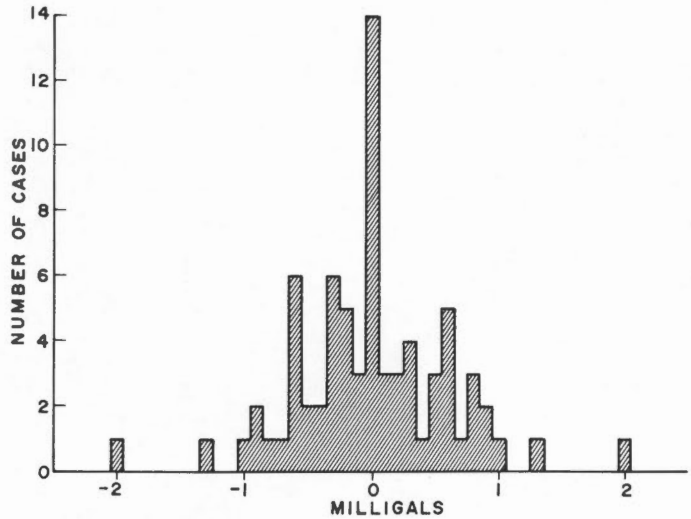

Figure 5. Histogram of the differences between Bouguer anomalies and mean values for stations reoccupied in the Gulf of St. Lawrence vs. number of cases.

DESCRIPTION AND DISCUSSION OF THE BOUGUER ANOMALY FIELD

Description of the Map

To facilitate the discussion of the gravity field, a simplified map of the Bouguer anomalies over the Gulf of St. Lawrence and surrounding area is presented in Figure 6. The map accompanying the report can be referred to for more detail.

The Bouguer anomalies have a range of more than 100 mgal, varying from less than -70 mgal in Quebec, north of Anticosti Island, to more than +30 mgal in west central Newfoundland. The regional value of the anomalies is 0 to -10 mgal over the southern Gulf and lowland areas of New Brunswick and Nova Scotia whereas the average value over Quebec, north of Anticosti Island, is -50 to -60 mgal. Intermediate regional values from -10 to -30 mgal occur between the western end of Anticosti Island and Newfoundland and over the highland areas of New Brunswick.

The underwater surveys done in 1962 and 1963 outlined several anomalies in the Gulf; the North Point and Magdalen Lows, a negative area over the eastern end of Prince Edward Island, and the Gaspé and Kingston Highs. An intense positive anomaly, the Sept-Iles High in the St. Lawrence River, was observed in 1962 during an isolated traverse (Figure 1). The 1966 and 1967 surveys have shown:

1. With the exception of the intense, nearly circular, gravity high south of Sept-

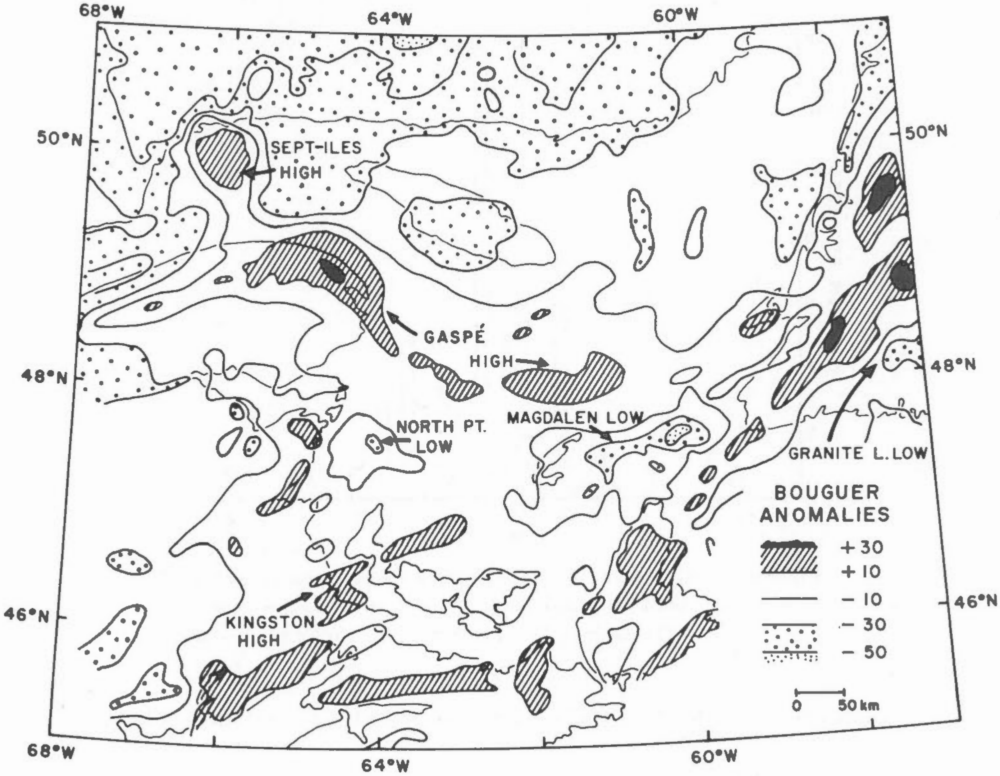

Figure 6. Simplified map of Bouguer anomalies for the Gulf of St. Lawrence and adjacent areas.

Iles, negative Bouguer anomalies extend over the northern part of the Gulf of St. Lawrence from the Saguenay River (west of the area shown in Figure 1), to the Strait of Belle Isle.

2. The Gaspé High trends toward southwestern Newfoundland but decreases in intensity about 60 miles west of Port-au-Port Peninsula.

3. The Magdalen Low increases in intensity to the northeast and closes near Cape Anguille, Newfoundland.

4. Positive anomalies over the southern end of the Long Range Mountains, Newfoundland continue southwest across the mouth of the Gulf toward positive anomalies over the Cape Breton Highlands.

The Regional Gravity Field

The locations of the density variations producing the changes in the level of the regional gravity field are not yet known. In the absence of any information other than the gravity data, the anomalous mass distributions may be postulated to lie somewhere between the surface of the earth and a depth approximately equal to the wavelength of the gravity variations being considered. For example, Tanner and Uffen (1960) suggested that the regional gravity field over the Gaspé Peninsula could be produced by any combination of the following sources: a variation in the thickness of near-surface, low-density sedimentary rocks; a variation in the thickness of high-density igneous rocks buried at a depth of about 4 miles; and a change in the position of the upper surface of a hypothetical intermediate layer lying below a depth of about 8 miles.

Although Carboniferous sedimentary basins in Nova Scotia and in southwestern Newfoundland and Devonian sandstones in Gaspé produce local minimums in the gravity field, Paleozoic sedimentary rocks apparently do not provide the major control of the Bouguer anomalies over the Gulf of St. Lawrence and adjacent areas (Goodacre and Nyland, 1966; Weaver, 1967). The results of recent seismic refraction surveys by the Geological Survey of Canada when available and combined with earlier seismic work (Willmore and Scheidegger, 1956; McConnell and McTaggart-Cowan, 1963) should provide important information about the structure of the sedimentary rocks in the Gulf and enable a more complete interpretation of the gravity field. A more probable source of the regional anomaly changes may be south within the lower crust and upper mantle. The available crustal seismic data (Ewing, et al., 1966) suggest that the crust under the southern portion of the Gulf of St. Lawrence is thicker and has a higher mean density than the crust under Anticosti Island and the Great Northern Peninsula of Newfoundland; and that the mantle under the lower Gulf has a higher density than the mantle under the area to the north. Weaver (1967) concluded that the seismic data were consistent, within the limits of their accuracy, with the regional gravity variations, provided that density variations occur within the upper mantle. The relationship between gravity and seismic data is not always straightforward, as is evident from the Hudson Bay Geophysical Survey of 1965 (Ruffman and Keen, 1967; Innes, et al., 1967), and considerably more seismic work, both deep and shallow, is required in the Gulf of St. Lawrence. In addition, drilling and a program of systematic rock-density sampling must be carried out in and around the Gulf of St. Lawrence before the regional gravity field can be explained with confidence.

The Gravity Anomalies in the Northern Portion of the Gulf of St. Lawrence

The Sept-Iles High, outlined in detail by the 1967 underwater gravity measurements, is an almost circular anomaly having a diameter of approximately 30 miles and a magnitude of about 60 mgal. This intense positive anomaly may indicate a large basic intrusion at the border of the Canadian Shield; anorthosite and gabbro, outcropping near Sept-Iles (Faessler, 1942) may reflect the source of the anomaly.

Except for the Sept-Iles High, the Bouguer anomaly field in the northern portion of the Gulf of St. Lawrence is generally more negative and has fewer irregularities than the gravity field over the central and southern parts of the Gulf. The negative Bouguer anomalies are characteristic of the Precambrian Shield and, as suggested by Weaver (1967), the boundary of the Grenville and Appalachian geological provinces is probably located immediately to the north of the Gaspé High and the positive anomaly on Port-au-Port Peninsula.

Local, relatively high, gravity anomalies observed about 60 miles northwest of Port-au-Port Peninsula, in the northeast corner of the Gulf, may be produced by heavy igneous and metamorphic rocks within the crystalline Grenville basement that probably underlies these areas. For example, the anomaly northwest of Port-au-Port Peninsula is similar in size and magnitude to a gravity high associated with an assemblage of gabbro, amphibolite and quartzite in the Johan-Beetz area of Saguenay County north of Anticosti Island (Grenier, 1957; Cooper, 1957).

The Gaspé High

The underwater gravity surveys of 1963 traced the Gaspé High, an arcute belt of positive anomalies (Figure 6) some 150 miles southeast from the Gaspé Peninsula to a point north of the Magdalen Islands. At this point the anomaly appeared to trend toward western Newfoundland. Goodacre and Nyland (1966) suggested that the Gaspé High was produced by rocks similar to the altered basic volcanic rocks of the Shickshock Series of Gaspé (Tanner and Uffen, 1960) and that the presence of this gravity feature in the Gulf tended to confirm the suggestion of King (1951) that the rocks of northwestern Newfoundland seem to be more closely related to those of Gaspé than those of Cape Breton Island and Nova Scotia. Weaver (1967) suggested that the positive anomaly over Port-au-Port Peninsula (Figure 6) may reflect basic rocks similar to those producing the Gaspé High and that the entire positive belt may mark the position of the Grenville-Appalachian boundary under the Gulf of St. Lawrence. Innes and Argun-Weston (1967) and others have pointed out that this boundary is generally flanked along its entire length by a negative anomaly belt to the north and west and a positive anomaly belt to the south and east. Although the trend of the Gaspé High toward Newfoundland is diminished almost to a 'saddle point' some 60 miles northeast of the Magdalen Islands, the recent gravity surveys have shown that this positive belt links up with the high over the Port-au-Port Peninsula. In addition, the recent underwater results have outlined a series of gravity minima north of the Gaspé High that extend across the map area at a latitude of approximately 49°30'N (Figure 6). Therefore the Gaspé High and flanking gravity lows to the north appear to be extensions of anomalies that are observed along the entire northwestern boundary of the Appalachian geological province. The negative anomalies north of the Gaspé High are not as pronounced as those along other portions of the Appalachian Front and their sources are uncertain. However the origin of both the positive and negative belts is probably due to lithological changes throughout the crust and, perhaps, in the upper mantle (Innes and Argun-Weston, 1967).

The Magdalen Low

The most negative Bouguer anomaly measured in the Gulf of St. Lawrence is the minimum value of -60 mgal for the Magdalen Low. Elsewhere in the Maritime Provinces, Carboniferous sedimentary basins estimated to be 4 miles deep, depress the gravity field to a value of -20 mgal; it is unlikely that the Magdalen Low is produced entirely by an exceptionally deep Carboniferous basin, as the available seismic data do not indicate an abnormal thickness of sediments between the Magdalen Islands and Cape Breton Island (George Hobson, personal communication). However, evaporites (Goodacre and Nyland, 1966) or other abnormally low density Carboniferous sediments may contribute to the Magdalen Low. Alternatively, Devonian granite beneath the Carboniferous sediments may contribute to the negative anomaly. Basic rocks similar to those observed on the Magdalen Islands (Obalski, 1903) could produce near-surface density variations that satisfy the observed short wavelength gravity variations. A comparison of the Magdalen Low with the Granite Lake Low, which lies to the east of Long Range Mountains in Newfoundland (Weaver, 1967), shows that the sizes, shapes and intensities of the anomalies are similar. The North Point Low is thought to outline another granite body to the west (Goodacre and Nyland, 1966; Bhattacharyya and Raychaudhuri, 1967). The geological structure of the area appears complex as the late-Paleozoic structures of the Appalachian orogeny cut across the earlier structural trends of the Acadian and Taconic orogenies. However a major portion of the Magdalen Low may be caused by a granite batholith that is part of a belt of Devonian granites extending from New Brunswick to Newfoundland.

The Gravity Field between Cape Breton Island and Newfoundland

A positive belt of Bouguer anomalies, generally higher than 10 mgal, trends southwest from the southern section of the Long Range Mountains of Newfoundland to the Cape Breton Highlands and reflects the presence of the heavy pre-Carboniferous basement complex. Although the belt is locally disturbed at the northern tip of Cape Breton Island where a thick sequence of sediments has been detected by seismic refraction profiling (George Hobson, personal communication) the gravity pattern suggests these two areas are structurally related. Magnetic and seismic investigations (Sheridan and Drake, 1968) also provide evidence for structural continuity of Cape Breton Island and southwest Newfoundland.

CONCLUSIONS

The results of the 1966 and 1967 underwater gravity surveys indicate the following:

1. Regional underwater gravity surveys can be made on a routine basis and provide data that are comparable in quality to those obtained on land.

2. The Bouguer anomaly field over the northern part of the Gulf of St. Lawrence is similar to that of the adjacent Precambrian Shield, and is more negative, on the average, than the gravity field in the southern part of the Gulf. The change in anomaly level, from negative to positive, in the central portion of the Gulf is believed to mark the boundary between the Grenville and Appalachian geological provinces.

3. An arcuate positive anomaly belt that traverses the Gulf of St. Lawrence from the Gaspé Peninsula to Port-au-Port Peninsula, Newfoundland is produced by basic rocks characteristic of the boundary of the Grenville and Appalachian geological provinces.

4. The Bouguer anomaly field reaches a minimum of -60 mgal near the Magdalen Islands. The depressed field may be produced by abnormally light, Carboniferous sediments or Devonian granitic rocks or by both.

5. A southwest-trending positive anomaly belt between southwestern Newfoundland and Cape Breton Island is believed to reflect the presence of the dense pre-Carboniferous basement, suggesting structural continuity between these two areas.

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Appendix

FIELD OBSERVATIONS, OBSERVED GRAVITY VALUES AND BOUGUER ANOMALIES FOR UNDERWATER GRAVITY STATIONS REOCCUPIED IN THE GULF OF ST. LAWRENCE

Station Number	Location		Observed Gravity (mgal)	Water Depth (ft)	Bouguer Anomaly (mgal)
	Latitude	Longitude			
Section A					
800662	45° 55'.2	61° 59'.3	980724.6	147	5.3
812862	45° 55'.2	61° 59'.3	980724.7	148	5.3
801962	46° 23'.2	61° 30'.9	980752.0	228	-13.2
811762	46° 23'.1	61° 30'.7	980750.5	228	-14.5
800162	45° 51'.0	62° 14'.1	980716.5	129	4.3
800262	45° 50'.7	62° 14'.1	980715.8	124	4.3
803362	47° 00'.2	62° 49'.2	980824.1	213	4.0
805562	47° 00'.2	62° 49'.2	980824.0	213	3.9
807962	47° 00'.2	62° 49'.2	980824.0	211	4.0
810162	46° 59'.5	62° 49'.8	980824.3	213	5.0
Section B					
794963*	47° 04'.7	61° 32'.8	980795.8	102	-25.9
796663*	47° 04'.8	61° 32'.9	980792.8	98	-28.9
794563*	47° 06'.0	61° 06'.9	980820.8	226	- 8.6
801563	47° 06'.3	61° 06'.3	980819.9	233	-10.3
791563	47° 07'.5	61° 43'.5	980808.6	92	-16.8
796763*	47° 07'.5	61° 43'.3	980809.8	105	-16.2
803763	47° 07'.5	61° 43'.5	980809.5	98	-16.2
794663*	47° 09'.2	61° 18'.2	980794.2	151	-36.5
801463	47° 09'.3	61° 17'.9	980794.3	157	-36.9
791263	47° 23'.0	61° 36'.2	980828.9	79	-19.2
793063*	47° 23'.1	61° 35'.9	980829.3	82	-19.0
801163	47° 22'.7	61° 36'.4	980829.5	79	-18.1
797963*	47° 25'.9	62° 22'.1	980852.4	197	- 5.5
799663*	47° 25'.9	62° 22'.1	980853.2	190	- 4.4

Station Number	Location Latitude	Location Longitude	Observed Gravity (mgal)	Water Depth (ft)	Bouguer Anomaly (mgal)
799563*	47° 30'.2	62° 06'.2	980852.0	131	- 9.3
802463	47° 30'.6	62° 05'.9	980850.0	134	-12.0
776363	47° 50'.1	63° 59'.0	980888.9	249	- 7.7
778863	47° 50'.0	63° 59'.1	980886.6	243	- 9.6
776163	48° 04'.5	63° 50'.6	980923.8	315	2.5
780263	48° 04'.3	63° 50'.7	980924.2	315	3.2
772063	48° 18'.3	64° 10'.2	980941.4	354	- 2.3
773563	48° 18'.1	64° 09'.3	980941.8	380	- 2.9
775863	48° 18'.3	64° 08'.8	980942.1	358	- 1.8
783463	48° 17'.9	64° 09'.2	980941.9	374	- 2.2
771663	48° 49'.0	64° 02'.1	981003.3	403	11.4
785563	48° 48'.9	64° 01'.8	981003.3	407	11.3
794763*	47° 12'.2	61° 27'.5	980824.5	118	- 9.2
801363	47° 11'.9	61° 28'.8	980823.7	125	- 9.9
794463*	47° 03'.7	60° 55'.8	980820.6	361	-11.6
796363*	47° 02'.0	60° 55'.7	980820.6	354	- 8.8
782463	48° 07'.2	62° 24'.0	980931.2	197	11.4
782463 rpt	48° 07'.2	62° 23'.0	980931.7	194	12.0
782463 rpt	48° 07'.1	63° 23'.4	980931.8	197	12.0
780963	47° 53'.4	62° 31'.8	980905.8	216	5.8
780963 rpt	47° 53'.5	62° 31'.8	980906.4	216	6.4
779563	47° 38'.3	62° 39'.9	980874.4	203	- 2.4
779563 rpt	47° 38'.3	62° 40'.1	980874.0	197	- 2.5
779563 rpt	47° 38'.2	62° 39'.9	980874.2	200	- 2.4
777463	47° 23'.8	62° 48'.6	980853.9	151	1.3
777463 rpt	47° 23'.0	62° 48'.9	980853.9	151	1.3
78463	48° 15'.2	62° 19'.3	980940.8	233	6.9
78463 rpt	48° 14'.8	62° 19'.5	980940.4	236	6.9
Section C					
523066	48° 45'.9	60° 10'.1	980995.3	996	-19.7
523066 rpt	48° 45'.9	60° 10'.1	980995.2	1008	-20.4

Station Number	Location		Observed Gravity (mgal)	Water Depth (ft)	Bouguer Anomaly (mgal)
	Latitude	Longitude			
525366	48° 38'.1	59° 13'.5	980963.3	216	- 3.5
525366 rpt	48° 38'.1	59° 13'.5	980963.0	216	- 3.8
524766	48° 55'.7	60° 17'.7	981002.6	924	-23.7
524766 rpt	48° 55'.8	60° 17'.7	981002.4	924	-24.0
524566	49° 00'.2	60° 39'.1	980983.8	480	-28.4
524566 rpt	49° 00'.2	60° 39'.1	980982.5	486	-30.0
527266	49° 06'.7	59° 57'.5	981019.6	852	-19.8
527266 rpt	40° 06'.1	59° 57'.5	981031.9	894	- 8.5
528366	49° 10'.4	59° 43'.9	981038.0	924	-10.2
528366 rpt	49° 10'.4	59° 43'.9	981037.7	924	-10.5
528466	49° 06'.8	58° 54'.6	980982.7	270	-29.5
528466 rpt	49° 06'.8	59° 54'.6	980986.2	294	-27.1
501466	47° 30'.8	60° 41'.9	980819.1	186	-45.7
501466 rpt	47° 30'.8	60° 41'.9	980824.1	186	-40.7
504966	47° 11'.5	60° 02'.2	980870.2	1032	- 5.3
504966 rpt	47° 11'.5	60° 02'.2	980870.7	1038	- 5.0
507466	48° 33'.8	62° 34'.8	981014.0	1362	- 0.1
507466 rpt	48° 33'.8	62° 34'.6	981013.3	1332	0.6
509866	48° 21'.1	61° 14'.5	981001.6	1326	8.2
509866 rpt	48° 21'.1	61° 14'.6	981001.6	1332	7.9
512566	48° 54'.9	62° 58'.2	981019.1	1272	-22.3
512566 rpt	48° 54'.9	62° 59'.2	981017.6	1278	-24.1
510766	48° 05'.1	59° 44'.2	980947.8	948	- 4.1
510766 rpt	48° 05'.1	59° 44'.2	980945.3	972	- 7.6
516666	48° 02'.2	59° 33'.5	980925.3	672	- 9.3
516666 rpt	48° 02'.2	59° 33'.5	980927.9	690	- 7.5
514966	48° 31'.0	60° 43'.5	981003.6	1266	- 1.9
514966 rpt	48° 31'.0	60° 43'.5	981005.0	1276	- 0.9
514966 rpt	48° 31'.0	60° 43'.5	981003.0	1276	- 2.9

Station Number	Location		Observed Gravity (mgal)	Water Depth (ft)	Bouguer Anomaly (mgal)
	Latitude	Longitude			
519966	48° 27'.5	60° 08'.7	980982.1	1098	-10.2
519966 rpt	48° 28'.2	60° 08'.7	980979.8	1116	-15.3
522266	48° 30'.1	59° 42'.1	980965.5	684	-11.3
522266 rpt	48° 30'.1	59° 42'.1	980964.9	636	- 9.7
Section D					
605467	49° 40'.6	64° 21'.0	981028.4	276	-34.3
605467 rpt	49° 40'.8	64° 21'.4	981027.6	264	-34.9
608867	50° 09'.6	64° 41'.2	981069.3	366	-40.7
608867 rpt	50° 09'.6	64° 41'.3	981069.4	342	-39.5
611867	49° 08'.0	66° 56'.4	980996.7	888	-46.2
611867 rpt	49° 08'.0	66° 56'.5	980999.0	900	-44.5
610467	50° 08'.0	65° 08'.0	981054.6	420	-55.6
610467 rpt	50° 07'.6	65° 08'.0	981052.6	420	-57.0
610867	49° 40'.2	65° 24'.0	981052.2	912	-39.8
610867 rpt	49° 40'.0	65° 24'.0	981051.6	912	-40.1
605167	50° 00'.0	64° 34'.6	981070.3	570	-35.1
608567	50° 00'.0	64° 34'.6	981067.2	504	-35.0
Section E					
808062	47° 05'.0	62° 34'.4	980822.5	248	- 6.4
797663	47° 04'.4	62° 35'.3	980820.9	213	- 5.5
808362	47° 29'.0	62° 33'.5	980859.6	252	- 5.5
798063	47° 28'.9	62° 33'.1	980860.8	246	- 3.9
809262	48° 15'.3	62° 19'.5	980938.9	244	4.8
784663	48° 15'.2	62° 19'.3	980940.8	233	7.4
809362	48° 07'.2	62° 23'.6	980928.4	220	7.5
782463	48° 07'.2	62° 24'.0	980931.2	197	11.4
809562	47° 53'.0	62° 31'.2	980905.4	241	4.9
780963	47° 53'.4	62° 31'.9	980905.8	216	5.8

Station Number	Location Latitude	Location Longitude	Observed Gravity (mgal)	Water Depth (ft)	Bouguer Anomaly (mgal)
809762	47° 38'.6	62° 40'.2	980873.8	221	- 4.3
779563	47° 38'.6	62° 39'.9	980874.4	203	- 2.4
770963	49° 17'.5	65° 45'.4	981047.9	623	3.2
611267	49° 17'.5	65° 44'.9	981047.9	600	4.3
788063	49° 39'.9	65° 50'.4	981057.0	758	-27.3
616867	49° 39'.0	66° 51'.0	981053.0	690	-26.8
Section F					
785663	48° 56'.1	63° 58'.8	981034.5	886	9.4
508266	48° 55'.0	64° 00'.1	981034.0	846	12.4
785763	48° 53'.4	63° 48'.2	981025.8	856	6.1
508166	48° 52'.9	63° 50'.6	981024.7	792	8.8
785963	48° 50'.8	63° 37'.0	981019.7	846	4.4
508066	48° 50'.0	63° 39'.8	981021.5	810	9.0
786063	48° 48'.0	63° 27'.0	981012.9	748	6.4
507966	48° 47'.9	63° 29'.6	981012.2	702	7.9
786163	48° 45'.4	63° 16'.3	981016.6	909	6.4
507866	48° 44'.7	63° 17'.8	981014.2	822	9.1
501466	47° 30'.8	60° 41'.9	980819.1	186	-45.7
618267	47° 31'.6	60° 42'.1	980822.1	180	-43.6
502066	47° 41'.6	60° 47'.9	980876.6	198	- 4.9
618357	47° 41'.5	60° 47'.5	980879.4	192	- 1.7
502566	47° 18'.1	60° 23'.8	980819.1	330	-33.4
618167	47° 17'.9	60° 24'.5	980819.1	282	-30.8
503566	47° 53'.9	61° 05'.5	980905.5	228	4.2
618467	47° 53'.4	61° 06'.2	980906.2	210	6.4
505866	47° 50'.9	59° 52'.6	980950.8	1608	-10.7
602267	47° 50'.8	59° 52'.5	980949.3	1560	- 9.8
505966	47° 54'.2	60° 03'.9	980952.7	1566	-11.7
602167	47° 53'.5	60° 02'.5	980948.4	1518	-12.8

Station Number	Location Latitude	Location Longitude	Observed Gravity (mgal)	Water Depth (ft)	Bouguer Anomaly (mgal)
506066	47° 57'.1	60° 14'.8	980963.4	1584	- 6.2
602067	47° 56'.6	60° 13'.6	980961.3	1542	- 5.6
506166	48° 00'.0	60° 25'.4	980963.8	1548	- 8.5
601967	47° 59'.5	60° 25'.7	980961.3	1500	- 8.0
517066	47° 48'.4	59° 42'.1	980939.9	1428	- 9.4
602366	47° 48'.0	59° 42'.7	980942.2	1416	- 6.0
526666	49° 16'.0	61° 06'.9	981006.5	696	-39.4
602467	49° 15'.2	61° 06'.0	981004.8	408	-26.4
526766	49° 20'.0	60° 51'.8	981032.1	768	-23.1
618567	49° 20'.0	60° 51'.8	981033.7	762	-21.2
529766	49° 28'.3	60° 23'.0	981047.3	978	-30.1
627367	49° 27'.8	60° 22'.4	981049.0	948	-26.2
530666	49° 10'.8	58° 42'.0	980986.3	276	-32.2
630067	49° 10'.5	58° 42'.0	980985.2	276	-32.8