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PRELIMINARY RESULTS OF GRAVITY SURVEYS OVER THE MACKENZIE BASIN AND BEAUFORT SEA

with maps: No. 117 — Wrigley - Providence
No. 118 — Arctic Red River - Norman Wells
No. 119 — Inuvik - Horton River

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DEPARTMENT OF ENERGY, MINES AND RESOURCES
OTTAWA, CANADA 1970

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ABSTRACT - Three Bouguer anomaly maps at a scale of 1:1,000,000 and contoured at 5 mgal intervals have been prepared from 6,100 gravity observations made in the Interior Plains and on the Beaufort Sea from latitude 60°N to 72°N.

The major features of the gravity field are: a gravity low over the Mackenzie Mountains which is attributed to a thickened sedimentary sequence and a deeper crust-mantle boundary; a relatively positive anomaly of 50 mgal striking north from Trout Lake to Great Bear Lake which reflects a ridge or trough of mafic rock within the Precambrian basement; a negative anomaly over the Mackenzie River delta of 55 mgal which results from the deposition of more than 21,000 feet of Cretaceous and Tertiary sediments; and a circular positive anomaly of 130 mgal situated south of Darnley Bay which is explained by a cone-shaped basic intrusion. Smaller variations in the gravity field in the Interior Plains may be attributed to changes in the depth to the Precambrian basement and density variations within the sedimentary column.

RÉSUMÉ - Trois cartes au 1: 1,000,000 des anomalies de Bouguer, avec courbes espacées de 5 mgal, ont été établies d'après 6,100 relevés gravimétriques effectués dans les Plaines intérieures et sur la mer de Beaufort, entre les 60° et 72° de latitude nord.

Les principales caractéristiques du champ de gravité sont: une dépression gravimétrique dans les monts Mackenzie, que l'on attribue à un épaississement des couches sédimentaires et à un abaissement de la zone de démarcation croûte-manteau; une anomalie relativement positive de 50 mgal à orientation nord entre le lac Trout et le Grand lac de l'Ours, qui reflète une crête ou un fossé de roches mafiques au sein du socle précambrien; une anomalie négative de 55 mgal dans le delta du Mackenzie, causée par le dépôt de plus de 21,000 pieds de sédiments du Crétacé et du Tertiaire, et une anomalie positive circulaire de 130 mgal au sud de la baie Darnley, que l'on attribue à une intrusion basique en forme de cône. Des variations plus faibles du champ de gravité dans les Plaines intérieures peuvent être expliquées par des variations de la profondeur du socle précambrien et des variations de la densité au sein de la colonne de sédiments.

INTRODUCTION

Between 1962 and 1969 some 6,100 gravity observations were made by Dominion Observatory field parties (Table I) in the Northwest Territories, from the British Columbia boundary northward to the Beaufort Sea, and westward from the Canadian Shield to the Mackenzie and Richardson mountains. The three maps accompanying this report show the observed Bouguer anomaly field over this portion of the Interior Plains and over a segment of the Beaufort Sea north of the Mackenzie River delta to latitude 72°N. The general area surveyed and the area covered by the maps is shown in the accompanying figure.

The veneer of lower Paleozoic sediments which forms the Interior Plains thickens westward from the border of the sediments and the Canadian Shield to 7,400 feet in the vicinity of Trout Lake and to 8,000 feet or more in the vicinity of the Peel River*. Local arches in the Precambrian basement have been recorded in the vicinity of Inuvik (Jeletzky, 1961, 1962), Fort Providence (Douglas, 1959) and west of Fort Simpson between the Mackenzie and Liard rivers (Schedule of Wells, 1963-68). The Franklin Mountains have a core of Precambrian rocks as do the northern Mackenzie Mountains (Aitken, Cook and Balkwill, 1970). On the flanks of the mountain ranges the lower Paleozoic sediments thicken to 10,000 feet. Cretaceous low-density sandstones and shales overlie the lower Paleozoic sediments around Great Bear Lake and in the Mackenzie and Arctic Red River valleys. Cretaceous to Recent sediments mask earlier formations in the Mackenzie River delta. Regional geological maps are available for the area south of latitude 64°N (Douglas, 1959; Douglas and Norris, 1959; 1960a, b; 1961; 1963), for the Richardson Mountains - Arctic Red River area (Norris, Price and Mountjoy, 1963) and for a large portion of the Interior Plains north of latitude 64° (Yorath, Balkwill and Klasson, 1969; Aitken et al., 1970).

This report describes the field techniques used to obtain the gravity data, the accuracy of the anomalies, the Bouguer anomaly field and its relation to the known geology.

FIELD PROCEDURES

Transportation and Logistics

Helicopters were the primary mode of transport: Bell helicopters, models 47G2, 47G4 and 47G4A, were used to survey the land and near-shore areas; the ocean survey (beyond 70 miles offshore) was done with larger jet helicopters, Bell models 204B and 205A. Station positions were planned to approximate a 7-mile grid. Every effort was made to position stations on points of known elevation as often as possible and to plan the traverses so that a gravity base reading would be taken at intervals of four to six hours.

The smaller helicopters required refuelling during the day at gas caches established in advance by fixed-wing aircraft (usually a Beaver). On an average day between 33 and 40 gravity readings were made by each observer.

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*Depths to basement have been abstracted from "Schedule of Wells, North of 60", a yearly publication of the Department of Indian Affairs and Northern Development.

Sketch map showing area of surveys. Borders of the gravity maps are outlined and each map is labelled according to its gravity map series (GMS) number.

The surveys on land areas averaged 25 per cent down time for weather and helicopter repairs. The weather was usually better in the spring (May and June) and deteriorated during the summer. Much of the work on the Beaufort Sea was done from a camp established on old polar ice about 150 miles north of Tuktoyaktuk. During the 23-day period spent at the ice camp (March 26 to April 18, 1969) the ice drifted more than 100 miles to the west. Poor weather, shortage of fuel and mechanical difficulties with the helicopters cut the working time at the ice camp to eight days.

Gravimeters

All control measurements and most of the measurements on the sea ice were made with LaCoste and Romberg gravimeters. The meters used on the ocean surveys

Table I

SURVEYS CONTRIBUTING DATA TO THIS REPORT

Year	Area of Survey	Party Chief	Number of Stations within Map Area
1962	Coppermine Area 66°N - 68°N 112°W - 120°W	R. W. Hornal	160
1966	Eastern District of Mackenzie 62°N - 70°N 100°W - 120°W	R. W. Hornal	660
1967	N. Alberta, Southern District of Mackenzie 54°N - 62°N 112°W - 120°W	J. B. Boyd	537
1969	Beaufort Sea Coastline - 74°N 128°W - 136°W	L. W. Sobczak	484
1969	Mackenzie Delta 68°N - Coastline 124°W - 136°W	L. W. Sobczak and R. W. Hornal	697
1969	Mackenzie Basin 60°N - Coastline 120°W - Mountains	R. W. Hornal	3,559

had a damping mechanism which could be applied as required. This mechanism reduced the accuracies of the individual readings from .01 mgal to .10 mgal but made it possible for an observer to read the instrument on the oscillating ice surface.

Since 1966 the LaCoste and Romberg gravimeters which belong to the Dominion Observatory have been carried whenever possible in vibration isolators to

reduce drift (Hamilton and Brule, 1967). Even with the isolators installed, strong vibrations in the jet helicopters caused large drifts or tares of up to 0.3 mgal per day in the meters used for the 1969 ocean work. This drift was greatly reduced in the Bell 205A helicopter by placing a thin slab of foam rubber below the gravimeter in the carrying case and horsehair padding beneath the gravimeter case. During the land surveys drift rates for the LaCoste and Romberg instruments remained below 1 mgal per month.

One temperature-controlled, damped Worden gravimeter (W573) was used on the Mackenzie Delta survey. This instrument was also used for work on the sea ice and performed quite well except after storms when the ice movement was still strong.

Worden prospector models were used to observe most of the gravity stations on the land surveys. As these surveys were done during the late spring and summer and the instruments were stored in unheated tents, temperature control was not a problem. The instruments were read at control stations at least twice a day to better determine drift. Drift rates rarely exceeded 0.1 mgal per hour for these instruments.

Elevations

In general the area covered by the map sheets has moderate relief but west of the Mackenzie River in the Mackenzie and Richardson mountains and along the east shore of Great Bear Lake station elevations varied by 2,000 feet.

Elevations were computed for most regional gravity stations from Wallace and Tiernan altimeter readings taken concurrently with the gravimeter readings and then corrected for changes in temperature, humidity and pressure patterns. Water levels were available for Great Slave Lake (513 feet), Great Bear Lake (511 feet) and the coastal areas. Additional elevations were available from level lines which have been run by members of the Surveys and Mapping Branch of the Department of Energy, Mines and Resources along the Mackenzie River between Great Slave Lake and the Beaufort Sea, from Great Slave Lake to Great Bear Lake, from Great Bear Lake north through Aubry Lake to Franklin Bay on the coast and from Aubry Lake east to Horton Lake, then north to Bluenose Lake and then east again to Coronation Gulf. Levels have also been run along the Mackenzie Highway, the boundary between the Northwest Territories and the provinces and south and east of Great Slave Lake along baselines and range lines of the Dominion Land Survey System. Secondary control was available in the form of earlier altimeter surveys and altitude profile recorder measurements. In mountainous areas or in areas where large gaps existed in the control data, the gravity survey parties established their own control network by making repeated altimeter ties.

Repeated elevation measurements suggest that elevation values on the Interior Plains are accurate to $\pm$ 20 feet but a few elevations in the mountains may be in error by as many as 50 feet.

Water Depths

Water depths for gravity stations over the Beaufort Sea were interpolated from Hydrographic Chart 7080 for shallow areas (depths less than 200 feet) and were determined by an Edo 9040-S24 echo sounder or by a Gifft sounder consisting of a

Gifft transceiver, a Hewlett-Packard counter and an oscilloscope for depths greater than 200 feet. Travel times for all soundings were converted to depths using the velocities of propagation for sound in sea water found by Matthews (1939).

The Gifft sounder digitally recorded the travel time in milliseconds. Normally, identical readings within a millisecond (2 feet) were obtained but when there were poor ice conditions, readings had a 5 ms scatter. When readings were not repeatable a new location would be chosen. Poor ice locations existed where the ice surface had been tilted due to the overlapping of ice sheets, where water mixed with snow was freezing on top of the ice, and where the upper surface was still wet over newly frozen leads. At a few locations, some false depths were observed either because unusual ice or bottom conditions existed or because the sounder was over shallow water where multiple reflections were picked up. Depths with uncertainties of over 200 feet were checked but little time was available during the survey to check smaller suspected errors which were indicated by irregularities in the Bouguer anomaly field.

Errors of 2 per cent of the water depth can be expected because of uncertainties in the propagation velocities, ice conditions and, in the case of the Edo echo sounder, instrument inaccuracies.

Horizontal Control

For land stations the original position was usually chosen at a readily identifiable point on a 1:250,000 topographic map. The observer would record the exact position on an office copy of the same map and the position would be scaled to an accuracy of 400 feet. In the 1962 survey it was necessary to use airphoto mosaics for point identification as only blue-line copies of the 1:250,000 maps were available at the time.

For the Beaufort Sea survey, a Decca Lambda chain was used for navigation and positioning. The Decca transmitters were positioned on Hooper Island, Atkinson Point and Herschel Island. The accuracy of most station positions on the Beaufort Sea was $\pm$ 750 feet. A few stations near the coast east of Tuktoyaktuk were positioned by dead reckoning and bearings as the Decca system has large errors along its baseline.

REDUCTION OF THE DATA

A gravity base network was constructed for 70 control stations, 40 of which are easily relocatable points within or adjacent to the survey area. The remaining 30 were secondary control stations, most of which were at gas caches established for special purposes during the survey. A total of 413 ties were made between the 70 stations. The gravity values for Yellowknife, Hay River and Port Radium were fixed during the adjustment as they were used in a previous adjustment for the eastern half of the District of Mackenzie (Hornal, 1970). The standard deviations of the gravity values for the main base stations were generally less than 0.05 mgal, the highest was 0.085 mgal.

Control for the work done over the Beaufort Sea from the drifting ice camp was obtained by several ties to shore control stations by one or both of the LaCoste and Romberg meters. These ties were made five times during the 18-day period that gravity observers were working from the ice camp.

The gravity observations were reduced to Bouguer anomalies using the method of Tanner and Buck (1964). For stations on the Beaufort Sea, the water layer (density = 1.03 g/cm^3) was replaced with a rock layer (density = 2.67 g/cm^3) of equal thickness.

The Eötvös effect caused by reading on the moving sea ice was omitted in the calculation of the Bouguer anomalies because usually it is small and difficult to obtain (additional time would be required to determine the velocity and direction of ice movement). This effect may be approximated by the following relation:

$$CE = 4.5\ V\cos\phi \quad \sin\alpha$$

where CE is the change in gravity in mgal, V is the velocity of the sea ice in km/hr, ϕ is the latitude, and α is the direction of travel. For example, if it is assumed that the sea ice at latitude 72°N is travelling due east at 0.1 km/hr, a value which is considered to be average, then this would introduce a 0.13 mgal error in the gravity reading.

Terrain corrections were made for several stations in the Franklin and Mackenzie mountains. The largest of these amounted to 13.5 mgal but most were less than 5 mgal. The maximum terrain correction for the stations on the Beaufort Sea would occur above the edge of the continental slope. For a slope of 3° the correction would be 2 mgal.

The accuracy of the Bouguer anomalies is largely dependent on the accuracy of the depth and elevation measurements. The uniform terrain of the Interior Plains and the continental shelf reduces the error due to these factors to a minimum in these areas. However, over the deep ocean and within the foothills errors due to depth and elevation are significant. Table II summarizes the maximum errors for various regions covered in the accompanying maps. In general the Bouguer anomaly values are probably accurate to ±2 mgal for 98 per cent of the 6,100 stations observed.

The principal facts for all gravity stations and descriptions of base station locations are available on request from the Gravity Division, Earth Physics Branch, Department of Energy, Mines and Resources, Ottawa.

Table II

ESTIMATED MAXIMUM ERROR IN BOUGUER ANOMALIES FOR VARIOUS REGIONS WITHIN THE SURVEY AREA

	Maximum Error (mgal)			
	Sea		Land	
Source of Error	Near Shore	Beyond	Plains	Foothills
Reading and Eötvös Effect	0.1	0.5	0.1	0.1
Position	0.6	0.3	0.2	0.2
Elevation	-	-	1.2	3.0
Depth	1.0	2.9	-	-
Terrain	-	2.0	0.5	5.0

THE BOUGUER ANOMALY MAPS

The Bouguer anomaly field has been contoured at intervals of 5 mgal and is shown on the accompanying maps (in pocket). The Bouguer anomalies range from -94 mgal to +127 mgal. The more negative anomalies are found in the Mackenzie Mountains and the Norman Range of the Franklin Mountains; the positive anomalies generally occur over the Beaufort Sea and over a circular structure, named here the Darnley Bay High, discovered south of Darnley Bay (Gravity Map Series 119).

In general the Bouguer anomaly values increase from south to north. The average Bouguer anomaly value for the Wrigley-Providence map area (GMS 117) is -40 mgal; for the Arctic Red River-Norman Wells area (GMS 118) it is -29 mgal and for the Inuvik-Horton River area (GMS 119) it is +7 mgal. This trend suggests an inverse relationship between the Bouguer anomaly values and the topography. There are several examples of Bouguer anomaly lows over topographic highs, e.g., Mackenzie Mountains, Horn Plateau, Grizzly Bear Mountain (situated on the peninsula between McVicar and Keith arms of Great Bear Lake). Some of the local topographic highs are hills of Cretaceous sandstones and shales which have a density of 2.30 g/cm^3 or lower. The amplitude of the Bouguer anomaly lows is much reduced when 2.30 g/cm^3 is used instead of 2.67 g/cm^3 in the Bouguer correction term for stations lying over these hills.

The trend to lower Bouguer anomalies over higher topography is reversed in the vicinity of the Peel River and southern Richardson Mountains (GMS 118). Over the Richardson Mountains, Bouguer values as high as +14 mgal are in direct contrast to values of -80 mgal found over the Mackenzie Mountains 150 miles to the east. The Richardson Mountains were not part of the Cordilleran Geosyncline but were formed during the Cretaceous and Tertiary periods from a narrow basin that developed within the Yukon Shelf (Jeletzky, 1961, 1962). The mountains are bounded to the east by a series of normal and strike-slip faults along which the movement has been concentrated. This area is still active (Jeletzky, 1961) and the Bouguer anomaly high may represent a major upwarp of the lower crust.

South of Great Bear Lake the Bouguer anomaly contours trend generally north-south parallel to the Mackenzie Mountains and the structural trend of the Slave geological Province. There is a large, relatively positive, anomaly of over 50 mgal which runs from the Trout River northward through Bulmer Lake and Keller Lake to McVicar Arm on Great Bear Lake. It has a steep gradient of up to 5.5 mgal per mile on its eastern flank and a more gentle gradient on its western flank. This anomaly has been named the Bulmer Lake High. The origin of this high is in the Precambrian basement. Three wells, Imperial Cartridge F-72 (63° 11'N, 120° 29'W), Imperial Triad Harris R. F-71 (62° 20'N, 120° 14'W) and Imperial Lac Tache C-35 (63° 44'N, 120° 37'W) drilled in 1960 along the strike of this anomaly, show no structure within the Paleozoic cover rocks which could account for such a large anomaly. Models that fit the observed field require a near-surface trough or ridge of high density (ρ = 3.0 g/cm^3) granulites or basic igneous rocks which is fault-bounded on the east, has a maximum thickness of 27,000 feet east of Bulmer Lake and then thins rapidly to the west.

A 25 mgal residual gravity low over the Cartridge Mountains between Lac Grandin and the Bulmer Lake High may result from either a thickened sequence of Cretaceous shales or a relatively low-density granite stock beneath the Paleozoic cover. This second possibility is more likely, as the Imperial Lac Tache C-35 well drilled on the flanks of this anomaly reached Cambrian sandstone (Old Fort Island Formation) at a depth of 1,405 feet indicating that the sedimentary column is not excessively thick under the anomaly.

West of the Mackenzie River the Bouguer anomalies decrease from -50 mgal to values of -70 mgal and locally to values of less than -90 mgal. The -50 mgal contour which encloses this broad low closely parallels the borders of the Mackenzie Mountains and the Norman Range of the Franklin Mountains. The negative anomaly is probably related to both the thicker sedimentary sequence found in these mountains and a deeper crust-mantle boundary beneath this regional topographic high. Local negatives of 10 mgal lie over synclines containing low density Cretaceous sandstone and shale, e.g., the Kotaneelee Syncline west of Fort Liard (Douglas and Norris, 1959).

North of Great Bear Lake and Fort Good Hope the Bouguer anomalies over the Interior Plains vary from -56 mgal to +11 mgal. Many of the local negative anomalies probably reflect thickening of the low density Cretaceous sediments whereas the more positive areas represent either thickening of the lower Paleozoic limestone and dolomite formations or, as is the case in the Inuvik area, arches in the Precambrian basement (Jeletzky, 1961). The density contrast between the carbonates and the Cretaceous clastic sediments is probably 0.3 or 0.4 g/cm^3. Therefore a change in thickness of the clastic sediments of 1,000 feet would change the anomaly by 4 to 5 mgal.

The anomaly field over the Mackenzie Delta varies from about 0 mgal at Inuvik to -57 mgal over Kugmallit Bay and increases to +75 mgal over the continental shelf and +125 mgal over the Beaufort Sea. The negative anomaly is an oval-shaped low about 100 miles wide and over 150 miles long which trends northeast from the present mouths of the Mackenzie River to the vicinity of Atkinson Point. It is broken by a northerly-trending, relatively positive anomaly of 30 mgal which is underlain by the Middle Channel of the Mackenzie River. This high is on strike with the Donna River Fault and may represent either a faulted horst or a local doming of Precambrian rocks and Paleozoic carbonates into the Cretaceous and Tertiary sediments, similar to the dome-shaped structures found farther south along the same fault (Jeletzky, 1961). To the north of the mainland the Bouguer anomaly gradient continues to the edge of the map area. Over the continental margin there is a plateau in the Bouguer anomaly values which corresponds to a large positive free air anomaly. The free air anomaly is similar to those observed further north along the same slope (Weber, 1963). The Bouguer anomaly gradient is much steeper (2.5 mgal per mile) north of Tuktoyaktuk than it is to the east (1.2 mgal per mile). If this steep gravity gradient reflects the rise in the crust-mantle boundary at the edge of the continental plate, then it would appear that the shelf to the north of the Mackenzie River has been built out over former oceanic crust.

The low over Kugmallit Bay and Richards Island can be explained by a basin of Tertiary and Cretaceous clastic sediments which attains a thickness of 21,000 feet ($\Delta \rho = -0.3$ g/cm^3). It is probable that this thick sequence thins out gradually to the north on the continental shelf but the negative anomaly due to these sediments is

obscured over the shelf by the positive anomaly due to the rising crust-mantle boundary.

East of the Mackenzie Delta along the coast there are two almost circular gravity highs. One of these has an amplitude of 45 mgal and is situated north of the present mouth of the Horton River. The other anomaly lies at the mouth of the Hornaday River and rises to a maximum value of +119 mgal, about 130 mgal above the regional field. This isolated anomaly, the Darnley Bay High, is the most striking anomaly in the area. Although no gravity observations were made over Darnley Bay the values on land suggest that the contours close over the bay and that the anomaly is circular and has a radius of 30 miles. Gradients on its flanks reach values of 9 mgal per mile.

This spectacular gravity feature is underlain by exposures of almost flat-lying late Precambrian to Quaternary sediments (Fraser, 1960; Yorath et al., 1969), most of which are of medium to low density. The gravity high is almost certainly caused by a basic intrusion which underlies these sediments. A few gabbroic dykes cut the exposures of the late Proterozoic sediments but no large body of basic rock is known in the area. The steepness of the gravity gradients and their abrupt change on the flanks of the anomaly suggest that the top of the body must be within a few thousand feet of the surface and that the flanks of the causative body must dip inward, i.e., the body probably has the shape of an inverted cone. If the contours are assumed to close over Darnley Bay then the application of Gauss' theorem shows that the excess mass of the causative body, independent of the shape and density chosen, must be 1.1×10^{13} tons. A good fit to the anomaly was obtained from a model shaped like an inverted cone of gabbroic composition ($\rho = 3.0$ g/cm^3) which intruded Precambrian rocks of density 2.7 g/cm^3 and which approached within 3 miles of the surface. The cone extended 24 miles into the crust, i.e., the apex of the cone probably reached the upper mantle. This density contrast of 0.3 g/cm^3 probably represents the lowest possible. Higher density contrasts can be used if the radius of the cone is increased and its height decreased. For a density contrast of 0.5 g/cm^3, i.e., the rock is ultrabasic, the best fit to the anomaly was obtained for a cone with a radius of 30 miles and a height of 12 miles.

To the east of Darnley Bay considerable basic igneous activity produced the Coppermine Basaltic Province of late Proterozoic age (Hornal, 1969). Within this province there are two gravity highs of similar areal extent but smaller amplitude which may be contemporaneous and of similar origin to the Darnley Bay High. They have been interpreted as basic plugs extending to depths of 15 miles or more and represent the channels up which basic material rose to the surface.

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