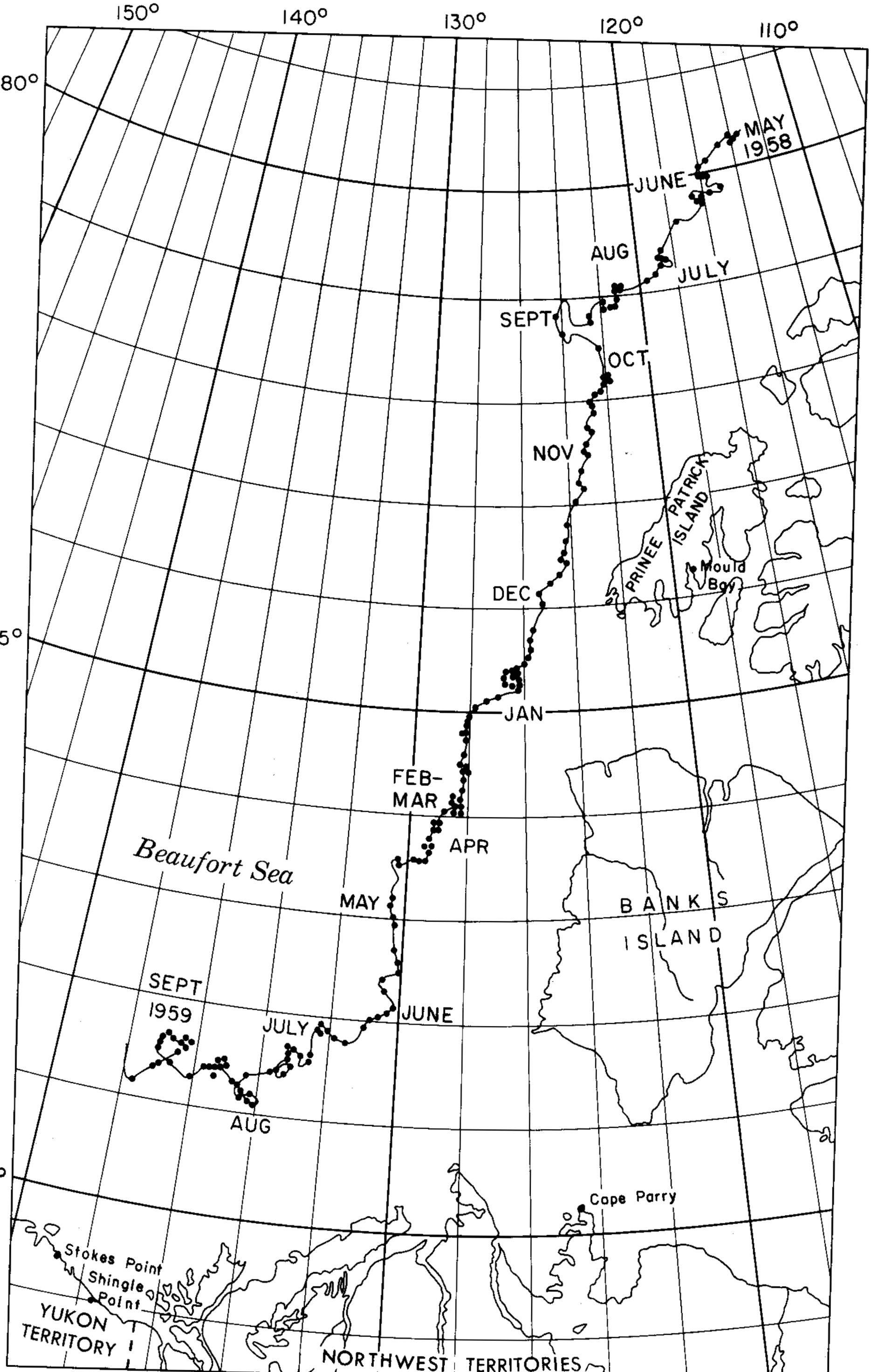

Fig. 1. Locations of Fletcher's Ice Island (T-3) during the period of gravity measurements. Known locations are shown by dots.

Papers

GRAVITY MEASUREMENTS IN THE BEAUFORT SEA AREA*

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Introduction

GRAVITY and other geophysical measurements (Plouff *et al.* 1961) were made on Fletcher's Ice Island (T-3) as part of studies for the International Geophysical Year, while the ice island was floating about 100 miles off the northwestern coastline of Canada (Fig. 1). The gravity data incorporated in this paper were collected by the following observers: Spencer Apollonio, Woods Hole Oceanographic Institute, from May 5 to 26, 1958; Donald Plouff, U.S. Geological Survey, from May 26 to October 11, 1958; David Craven and David Prentiss, Arctic Institute of North America, from October 11, 1958 to April 11, 1959; D. B. Jackson, U.S. Geological Survey, from April 11 to September 1, 1959; and R. R. Wahl, U.S. Geological Survey, from September 1 to 29, 1959. Gravity was measured twice daily during the entire period.

Gravity ties were made to Thule, Greenland, on May 5, 1958, September 20, 1958, and April 11 and 28, 1959. A tie was made in one direction to Barrow, Alaska, on September 29, 1959. The base station in Thule is located in the southeast corner of hangar three (building 623), where the value of gravity is 982,928.0 milligals (Woollard and Rose 1963, p. 93). D. B. Jackson established an additional station in hangar one (building 1090) by tying to hangar three; the value of gravity is 982,934.3 milligals. The station at Barrow is located at the site of Butler building 353 of the Arctic Research Laboratory, where the value of gravity is 982,699.6 milligals (Woollard and Rose 1963, p. 24).

The North American gravity meter 113a (constant 0.2130 milligals per dial unit) was used for most of the gravity observations at the base station on T-3. The Worden gravity meter E-340 (constant 0.2264 milligals per dial unit) was used for local gravity surveys on T-3 as well as for making ties to the station at Thule on April 11 and at Barrow on September 29, 1959. Observations with the Worden gravity meter were relied on at the base station also during the interval between April 11 and June 3, 1959, when a relay, controlling the temperature of the North American instrument, was malfunctioning.

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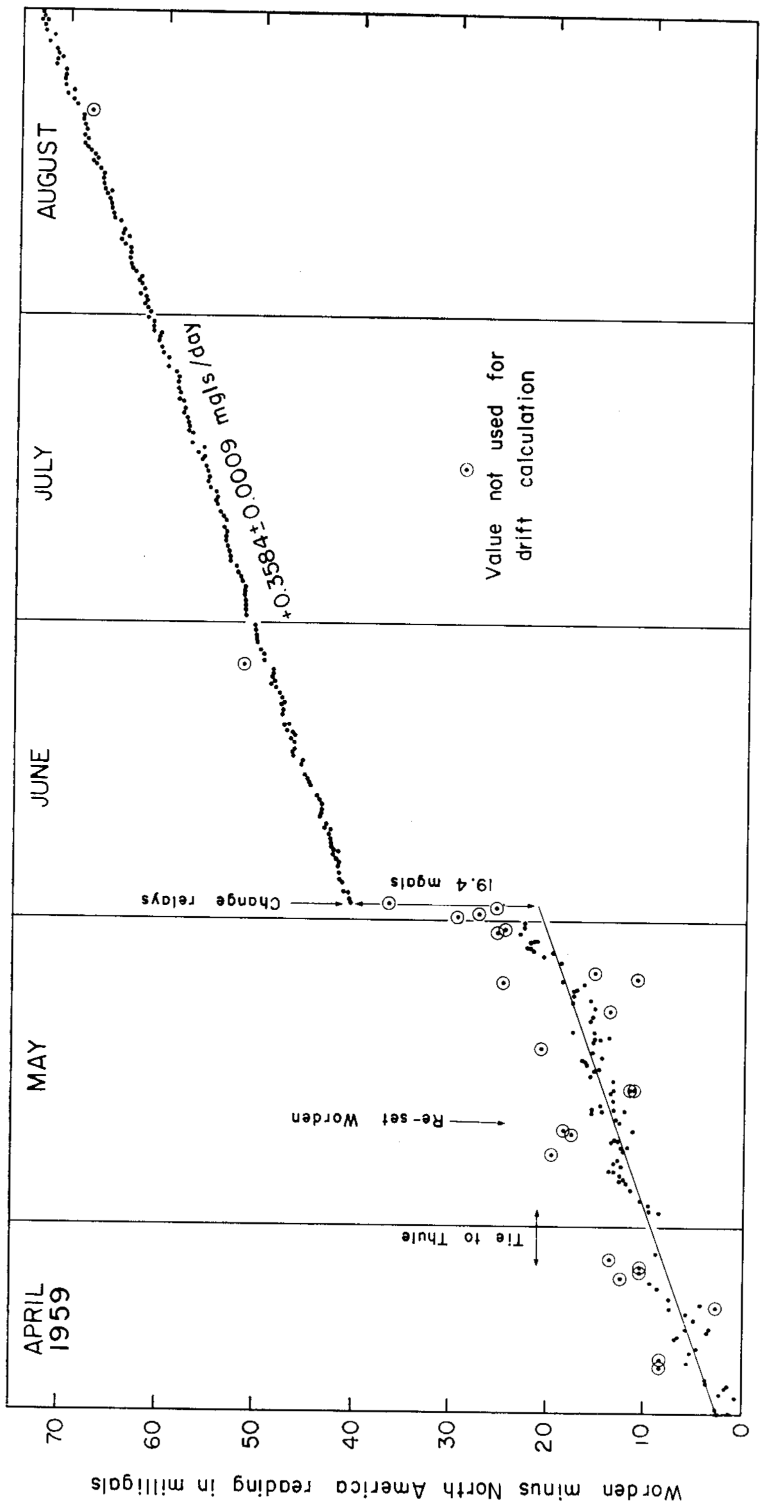


Fig. 2. Difference in drift between the Worden and North American gravity meters, 1959.

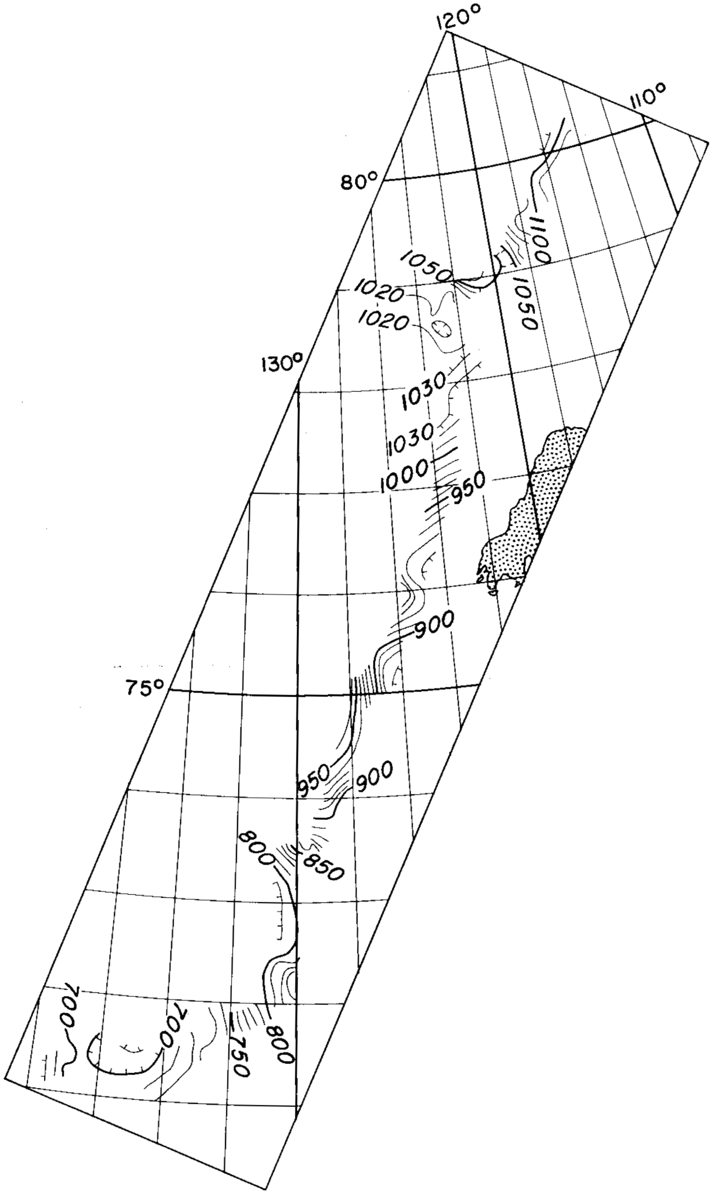


Fig. 3. Map of observed gravity. Interval 10 milligals. Add 982,000 milligals to convert to absolute value. Corrected to sea-level. Hachures on low side of contours.

By comparison of readings of the two instruments, the period during which the North American gravity meter was not dependable and the drift rate for the Worden gravity meter were determined (Fig. 2). The drift rate for the North American gravity meter has been recognized as nearly zero. For example, the difference in readings between ties to Thule in May and September 1958 corresponded to a change of less than one milligal. However, the North American gravity meter is subject to large shifts of datum, probably owing to mechanical or thermal shock, as indicated by the change on June 3, 1959, and by the occurrence of an error of closure of 20 milligals between ties to Thule in September 1958 and April 1959. Gravity readings recorded between February 25 and April 2, 1959, a period when the island was nearly at the same position, exhibit a scatter of less than 0.4 milligal. Therefore, the malfunction of the relay and a corresponding shift of gravity datum probably occurred between April 2 and April 11, 1959.

Observed gravity values corrected to sea-level were calculated and contours were drawn along the course of T-3 (Fig. 3). According to the errors of closure the accuracy of the observed gravity values is 1 milligal for the period from May to October 1958; about 20 milligals from October 1958 to May 1959; and 2 milligals from May to September 1959. Except for the intermediate period, greater accuracy would be superfluous, inasmuch as the island positions at which the gravity values are plotted are not known closely enough to warrant a higher degree of accuracy (Figs. 1 and 3).

Table 1. Representative gravity values.

Locality		*Error*	*Observed gravity*	*Free air anomaly*	*Gravity error*	*Ocean depth*†	*Bouguer anomaly*
Latitude north	*Longitude west*	*(miles)*	*(cm./sec.²)*	*(mgls.)**	*(mgls.)*	*(metres)*	*(mlgs.)*
71° 15′	137° 15′	3	982.683	−3	3	1555	104
71° 37′	136° 35′	2	.705	0	2	1965	135
71° 17′	136° 00′	2	.699	12	2	1265	99
71° 25′	135° 00′	2	.692	−2	2	1345	90
71° 24′	134° 05′	3	.704	11	2	995	79
71° 38′	133° 00′	2	.722	16	2	1145	95
71° 51′	132° 00′	2	.747	30	2	1130	110
72° 00′	131° 00′	2	.801	76	2	820	132
72° 30′	130° 00′	3	.803	51	2	1035	122
72° 59′	130° 25′	2	.791	15	2	1855	142
73° 34′	129° 50′	2	.863	57	1	880	117
73° 58′	129° 05′	2	.918	93	2	420	122
74° 30′	128° 15′	2	.946	95	20	1245	122
75° 00′	128° 00′	2	.964	91	20	1250	117
75° 17′	126° 15′	3	.874	−12	20	1295	15
75° 42′	125° 45′	4	.917	12	20	1285	39
76° 19′	124° 35′	6	.908	−22	20	760	−2
76° 50′	124° 10′	6	.942	−9	18	980	13
77° 16′	123° 30′	5	.994	26	18	915	46
77° 43′	122° 55′	4	983.031	45	15	1325	75
78° 00′	122° 40′	2	.030	33	13	1275	60
78° 28′	122° 20′	2	.014	1	2	1120	78
78° 48′	124° 10′	7	.016	−10	4	2390	154
78° 44′	122° 40′	2	.018	−5	1	2090	138
79° 00′	121° 00′	3	.058	26	1	2160	174
79° 04′	119° 40′	1	.051	17	1	2050	158
79° 14′	118° 30′	2	.067	27	1	1905	158
79° 34′	118° 00′	4	.086	35	4	1660	149
79° 41′	116° 20′	2	.112	57	1	1165	137
79° 58′	115° 40′	1	.108	46	1	1165	126
80° 08′	115° 40′	3	.090	22	2	1360	116
80° 17′	114° 10′	1	.106	33	1	1170	113

*1000 milligals = 1 cm./sec.².
†Interpolation between depths from seismic measurements.

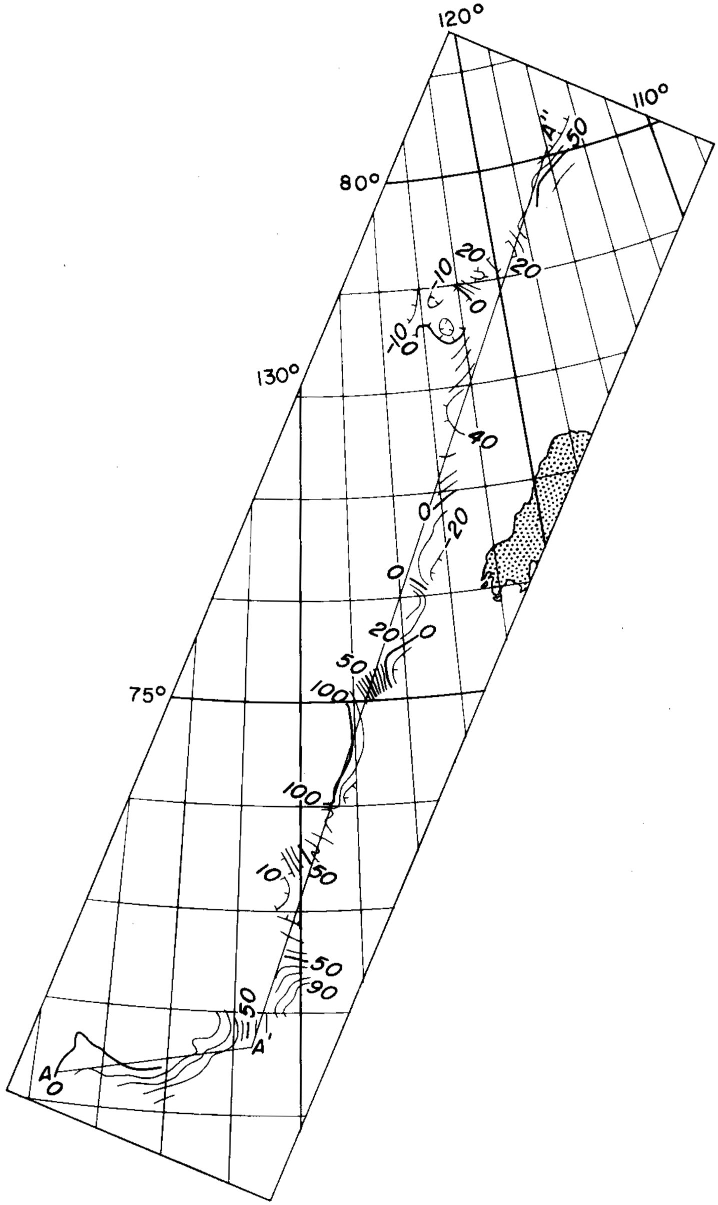


Fig. 4. Map of free air anomaly. Interval 10 milligals. Hachures on low side of contours.

Free air anomaly

The value of the theoretical gravity calculated using the International Gravity Formula of 1930 (Nettleton 1940, pp. 142-3) was subtracted from the value of the observed gravity to obtain the free air anomaly at the base station. The changes in the contoured values of the free air anomaly along the path of the island (Fig. 4) presumably correspond to lateral changes in density below the island without being obscured by the normal increase of the gravity to the north, as on the map of observed gravity.

The accuracy of contouring the free air anomaly was improved significantly during 1959 when the Worden gravity meter was used to conduct local surveys. A total of 62 sets of readings was taken for networks of three to nine field stations, separated by distances of 3,800 metres or less. The relative value of the free air anomaly was calculated for each field station after corrections were made for change in reading at the base station, relative altitude, and relative latitude. The average direction and magnitude of the maximum increase of the free air anomaly were determined for each set of readings.

The error associated with the calculation of the free air anomaly is a combination of the error in the value of the observed gravity and the error of interpolation between known locations of the island (Table 1). Mislocation in a north-south direction introduces an error of 0.5 to 0.9 milligal per nautical mile from the north edge to the south edge of this area. The largest errors correspond to the period when the 20-milligal misclosure occurred and to the period in September and October 1958, when only five positions for the island were determined.

The free air anomaly may be changed appreciably, though consistently, if the parameters in the International Gravity Formula of 1930

$$g = g_e\ (1 + B\ \sin^2\phi - C\ \sin^2 2\phi)$$

are revised, where the theoretical gravity g, in cm./sec.^{2} at sea-level, is expressed in terms of the latitude, and the average value of the gravity at the equator is g_e, 978,049 milligals. The constants are

$$B = 2.5m - f - 1.214\ mf$$

and

$$C = 0.625\ mf - 0.125\ f^2,$$

where

$$m = \frac{\omega^2 a}{g_e} \quad \text{and} \quad f = \frac{a - b}{a}.$$

The angular velocity of the earth is ω, the equatorial radius in metres is a, and the radius at the pole is b (Lambert 1945, p. 366).

By international agreement in 1924 Hayford's values (Hayford 1910, p. 77) were accepted for a and f from measurements in the U.S.A.

Thus

$$a = 6{,}378{,}388 \text{ metres and } f = 1/297.0.$$

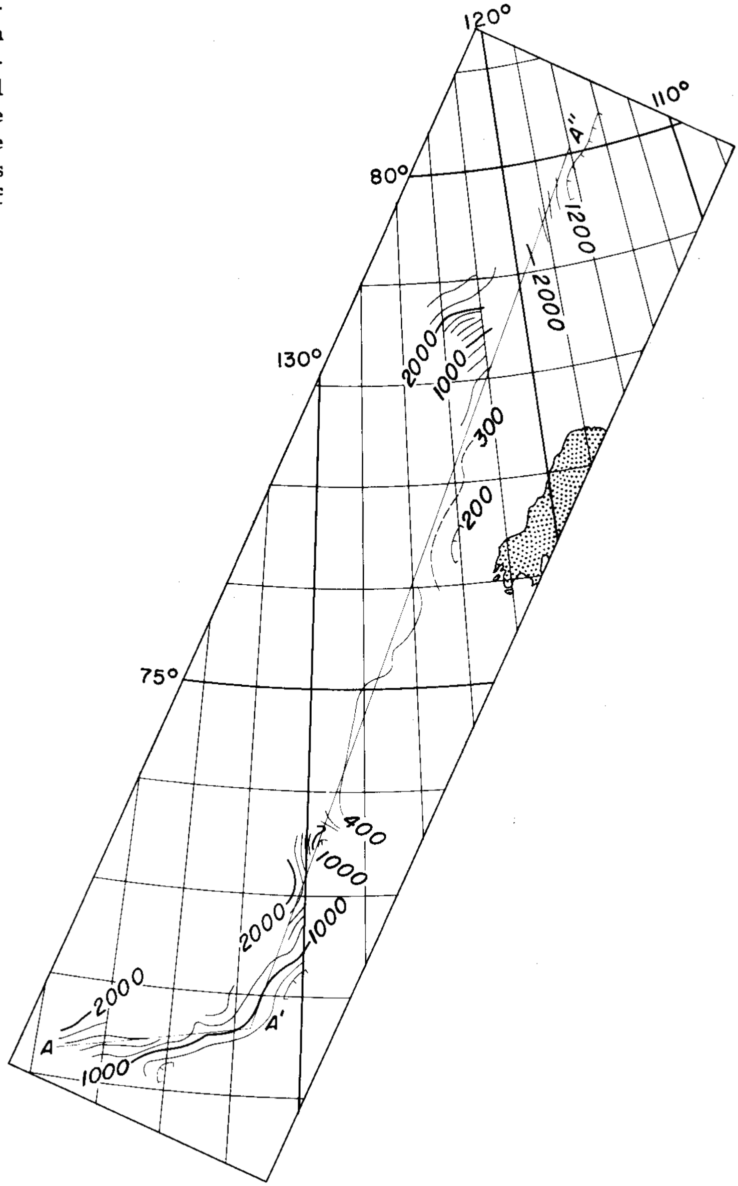
Other values have frequently been suggested for these constants. The equatorial radius a, and the value of gravity at the equator, g_e, seldom are changed appreciably in the fifth significant figure, whereas the polar flattening f changes in the third significant figure.

If the quantities m, a, ω, *and* g_e are considered fixed, and only the first order changes in f are considered,

$$\Delta g_f \cong -\ 978.049\ (\Delta f)\ \sin^2\phi,$$

where the change in flattening is Δf and the corresponding change in g is Δg_f. Fischer (1960), for example, has obtained a value of $f = 1/298.3$ from satellite studies. This value nearly is a minimum compared with other proposed values the flattening (Heiskanen and Vening Meinesz 1958, p. 78;

Fig. 5. Bathymetric map (from seismic measurements). Interval 200 m. (dashed line for intermediate values). Hachures on low side of contours.



Kaula 1959, Fig. 4). Thus, in this case,

$$\Delta g_f \cong +14.4 \sin^2\phi,$$

where Δg_f is expressed in milligals. The theoretical gravity would be increased and the free air anomaly decreased by 12.7 milligals at 70°N. and by 13.9 milligals at 80°N. This correction would have little effect on the anomaly pattern, but the datum would be shifted towards zero from an average of about +35 milligals to +22 milligals.

Bouguer anomaly

To make the Bouguer correction, a hypothetical rock, the density of which is 2.67 gm./cm.^{3}, is substituted for the sea water, which has a density of 1.03 gm./cm.^{3}. A density of 2.67 gm./cm.^{3} is used for the present study to standardize the resulting maps and to compare them with the existing maps. The effect of departures from this assumed density can be considered part of the interpretation. The Bouguer anomaly

$$B.A. = F.A. + 0.0686\,D,$$

where *F.A.* is the free air anomaly and *D* the estimated depth in metres to the ocean bottom as interpolated between the seismic measurements (Fig. 5). The resulting contoured values of the Bouguer anomaly along the path of the island (Fig. 6) are less accurate than the free air anomaly owing to the uncertainty of the interpolated depths.

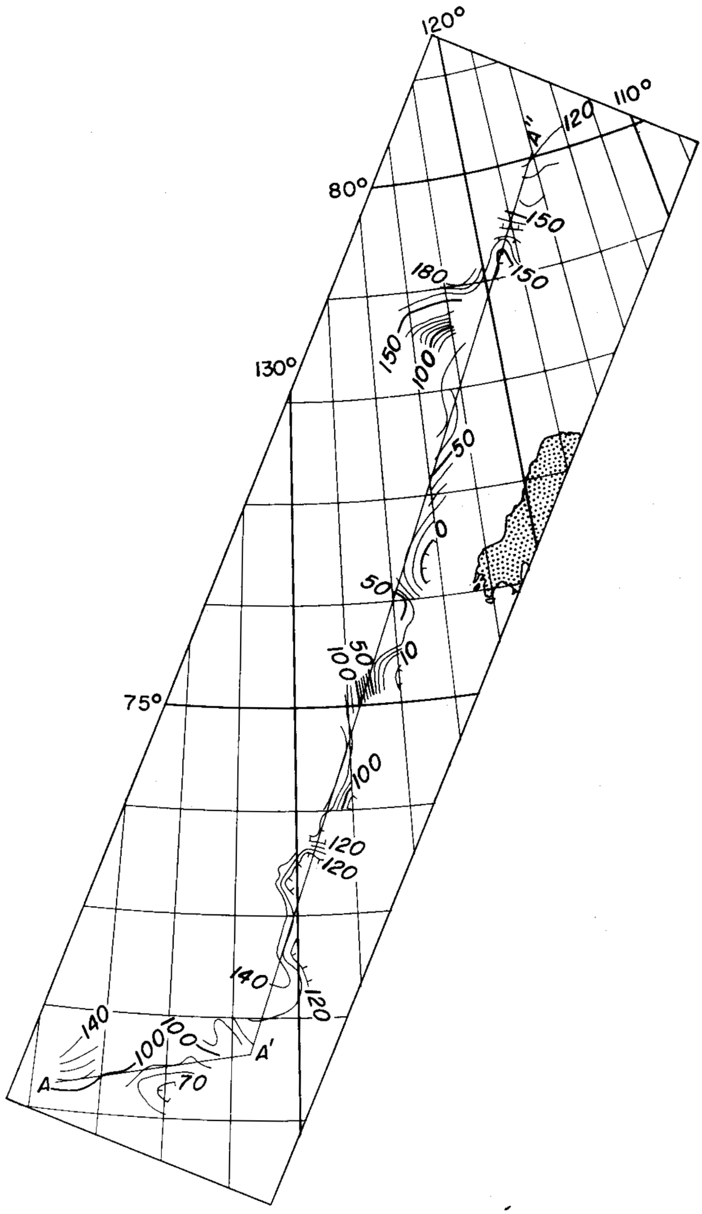
Interpretation

The average density of the rocks below the ocean bottom, where they consist of relatively young sedimentary rocks, may be appreciably lower than 2.67 gm./cm.^{3}. Large thicknesses of sedimentary strata are known in the adjacent arctic coastal plain of Canada (Fortier 1957, pp. 433-8; Tozer 1961), and a layer of rock with a relatively low seismic velocity of about 2 km./sec., usually associated with poorly consolidated sedimentary rock, has been reported in a deeper part of the Arctic Ocean (Crary and Goldstein 1957, p. 193). The only evidence, however, that the assumed density of 2.67 gm./cm.^{3} is too high occurs near the local topographic low point P (Fig. 7). Apparently, calculation of the Bouguer anomaly has overcompensated for the effect of the local submarine valley, but no appreciable free air anomaly low occurs at this locality. The apparent overcompensation at point P is primarily the result of errors in the interpolated location of seismic and gravity measurements between the assumed positions of the island (Figs. 1, 5, and 6) and of errors in the process of independently contouring the seismic and gravity maps on which the arbitrary profile is drawn.

In the absence of local isostatic compensation or correlation of topography with geologic structure one would expect that lows of free air gravity occur over submarine valleys and relative highs above hills. Along an arbitrary profile the free air anomaly nearly parallels the topography to the south of 73°15′N. but bears little relation to the topography to the north of this latitude (Fig. 7).

No attempt was made to estimate the densities of rocks near the ocean bottom in the manner of Crary and Goldstein (1957, pp. 199-201), inasmuch as the variations of gravity are controlled to an indeterminate degree by variations in density of rocks below the level of the irregularities of the sea bottom. Rocks below the ocean bottom vary laterally in density at several localities. The gravity anomalies between 76°N. and 78°N. and the gravity gradient near 75°N. (Fig. 7) correspond to contrasts in density of large

Fig. 6. Map of Bouguer anomalies. Interval 10 milligals. Hachures on low side of contours.



masses of rock below the ocean bottom. The uncertainties of position and the nearly one-dimensional character of the gravity coverage limit a quantitative interpretation of the relative densities and configurations of subbottom rocks.

Near 75°N. a 120-milligal increase of gravity indicates an increase in density of subbottom rocks towards the southwest (Fig. 4). A semi-infinite horizontal slab with a vertical edge at the centre of the gravity gradient may be hypothesized to approximate the shape of the anomalous mass of rock to the southwest. If a single contrast in densities is used, the thickness of the slab is 5.6 km. for a contrast of 0.1 gm./cm.^{3} or 1.4 km. for a contrast of 0.4 gm./cm.^{3}, to account for the total change of 120 milligals. It is not possible to determine unique values for the density contrast or for the depth to the top of the slab.

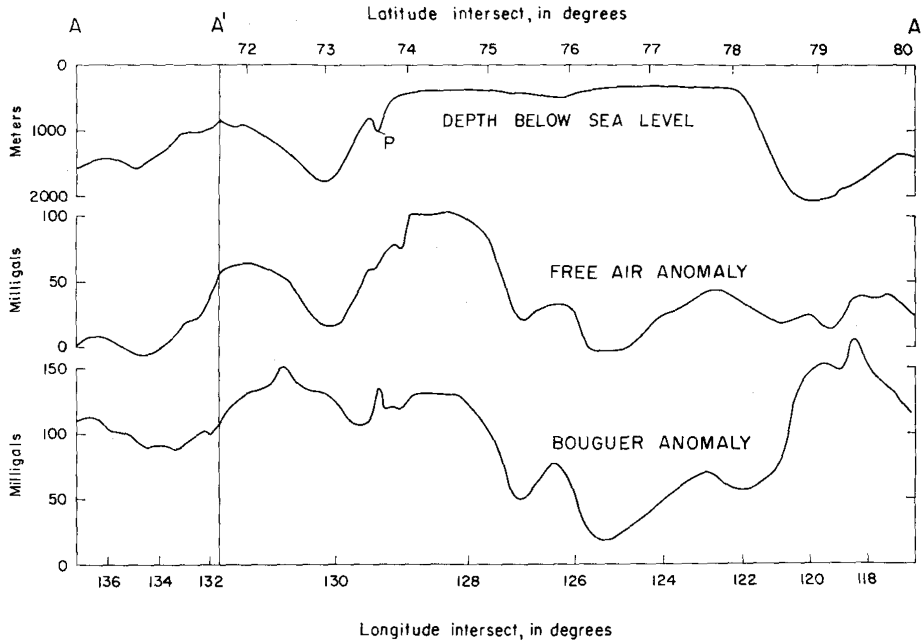


Fig. 7. Profiles along the line A-A'-A". See Figs. 4, 5, and 6.

Table 2. Other measurements of gravity in the Beaufort Sea area.

Locality		*Free air*	*Ocean*	*Bouguer*
Latitude north	*Longitude west*	*anomaly (mgls.)*	*depth (metres)*	*anomaly (mgls.)*
74° 47′	143° 38′	−6	3520	236
74° 45′	138° 40′	−17	3838	246
73° 22′	150° 55′	−15	3457	222
75° 53′	142° 10′	−11	3739	246

There is a general increase in the value of the Bouguer anomaly away from land (Fig. 6). Converting other gravity and seismic measurements in the Beaufort Sea (Crary *et al.* 1952, p. 215) to the Bouguer anomaly demonstrates that this increase continues farther offshore (Table 2). Correlation with gravity measurements in Canada (Woollard and Rose 1963, p. 92; Ostenso 1962, Fig. 16), however, is impractical because of the long distance of T-3 from shore (Table 3). Large positive values of the Bouguer anomaly, increasing with distance from shore, which correspond to diminishing depth to the Mohorovicic discontinuity, are characteristic of a normal ocean basin (*see*, e.g., Heiskanen and Vening Meinesz 1958, p. 201).

Table 3. Free air and Bouguer anomalies calculated at gravity stations established in Canada.

*Locality**	*Free air anomaly (mgls.)*	*Bouguer anomaly (mgls.)*
Mould Bay	8	7
Stokes Point	−4	−4
Shingle Point	−32	−32
Cape Parry	3	2

*See Fig. 1.

References

Crary, A. P., R. D. Cottell, and J. Oliver. 1952. Geophysical studies in the Beaufort Sea, 1951. Trans. Am. Geophys. Union 33:211-6.

Crary, A. P., and N. Goldstein. 1957. Geophysical studies in the Arctic Ocean. Deep-sea Res. 4:185-201.

Fischer, I. 1960. An astrogeodetic world datum from geoidal heights based on the flattening $f = 1/298.3$. J. Geophys. Res. 65:2067-76.

Fortier, Y. O. 1957. The Arctic Archipelago. *In* Geologic and economic minerals of Canada. Geol. Surv. Can. Econ. Geol. Ser. 1, 4th ed., pp. 393-442.

Hayford, J. F. 1910. Supplementary investigation in 1909 of the figure of the earth and isostacy. U.S. Coast and Geodetic Surv. 80 pp.

Heiskanen, W. A., and F. A. Vening Meinesz. 1958. The earth and its gravity field. New York: McGraw-Hill, 470 pp.

Kaula, W. M. 1959. Statistical and harmonic analysis of gravity. J. Geophys. Res. 64:2401-21.

Lambert, W. D. 1945. The International Gravity Formula. Am. J. Sci. 243-A:360-92.

Nettleton, L. L. 1940. Geophysical prospecting for oil. New York: McGraw-Hill, 444 pp.

Ostenso, N. A. 1962. Geophysical investigations of the Arctic Ocean Basin. Univ. Wisc. Geophys. Polar Res. Cent., Res. Rept. 62-4.

Plouff, D., G. V. Keller, F. C. Frischknecht, and R. R. Wahl. 1961. Geophysical studies of IGY Drifting Station Bravo, T-3, 1958 to 1959. *In* Geology of the Arctic. Toronto: Univ. of Toronto Press, 1:709-16.

Tozer, E. T. 1961. Summary of account of Mesozoic and Tertiary stratigraphy, Canadian Archipelago. *In* Geology of the Arctic. Toronto: Univ. of Toronto Press, 1:381-402.

Woollard, G. P., and J. C. Rose. 1963. International gravity measurements. Tulsa: Soc. Explor. Geophysicists, 518 pp.