GRAVITY MEASUREMENTS ON THE BARNES ICECAP, BAFFIN ISLAND*

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During the summer of 1950 I was sent north by the Dominion Observatory to make gravity observations as a member of the Arctic Institute's Baffin Island Expedition.[1] The main party was flown to Clyde, in east Baffin Island, in May 1950 by the R.C.A.F., and was later taken to the Barnes Icecap, 100 miles inland, by the expedition's Norseman aircraft. Return transportation was provided by the Department of Transport's vessel, the *C. D. Howe*, which also made stops at Pond Inlet and Arctic Bay, where regional gravity stations were established.

The gravity work on the expedition aimed at making a survey of the southeastern lobe of the Barnes Icecap, which is roughly 20 miles square, and at establishing as many regional gravity stations as possible. The objects of the survey were to attempt to determine the thickness of the ice and to outline the topographical features of the underlying rock surface.

Figure 1, which has been prepared from a preliminary base map drawn for the 8 miles to 1 inch map, shows the seven traverses, totalling 45 miles in length, along which gravity has been measured. The starting point of the survey was from Camp A, which lies approximately in the centre of the southeastern lobe of the ice cap. Three main gravity traverses AB, AC, and AD, each approximately 10 miles in length, were made from this point to the edge of the ice cap. Three shorter traverses EF, GH, and IJ, near the tip of the lobe, and another, KL, near its northern limit, were made to see if they would show evidence of subglacial valleys.

Field Methods

An engineer's transit and rod were used to locate the gravity stations and to measure their relative elevation. The stations are about 3,200 feet apart on the longer traverses and about 600 feet apart on the shorter ones. Rod readings could be estimated to one-tenth of a foot so that accumulated error on each of the traverses is not likely to exceed one foot. The absolute elevation for each station may be in error as much as ten per cent, since all elevations are relative to the elevation of Camp A, which was determined from a comparison of a number of aircraft altimeter readings taken at that point and at sea level. However, error in the absolute elevation in no way affects the computed ice thickness as only differences in elevation are used in the reduction.

The gravity measurements were made with a Worden gravimeter No. 44, which is light and sturdy; and therefore particularly well suited for a survey of this kind in which the long traverses had to be covered on foot. It is a

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[1]Led by Mr. P. D. Baird and supported by the Institute with funds provided through the U.S. Government. For general accounts of the expedition see *Arctic*, Vol. 3 (1950) pp. 131–49, and *Can. Geogr. J.* Vol. 42 (1951) pp. 212–23.

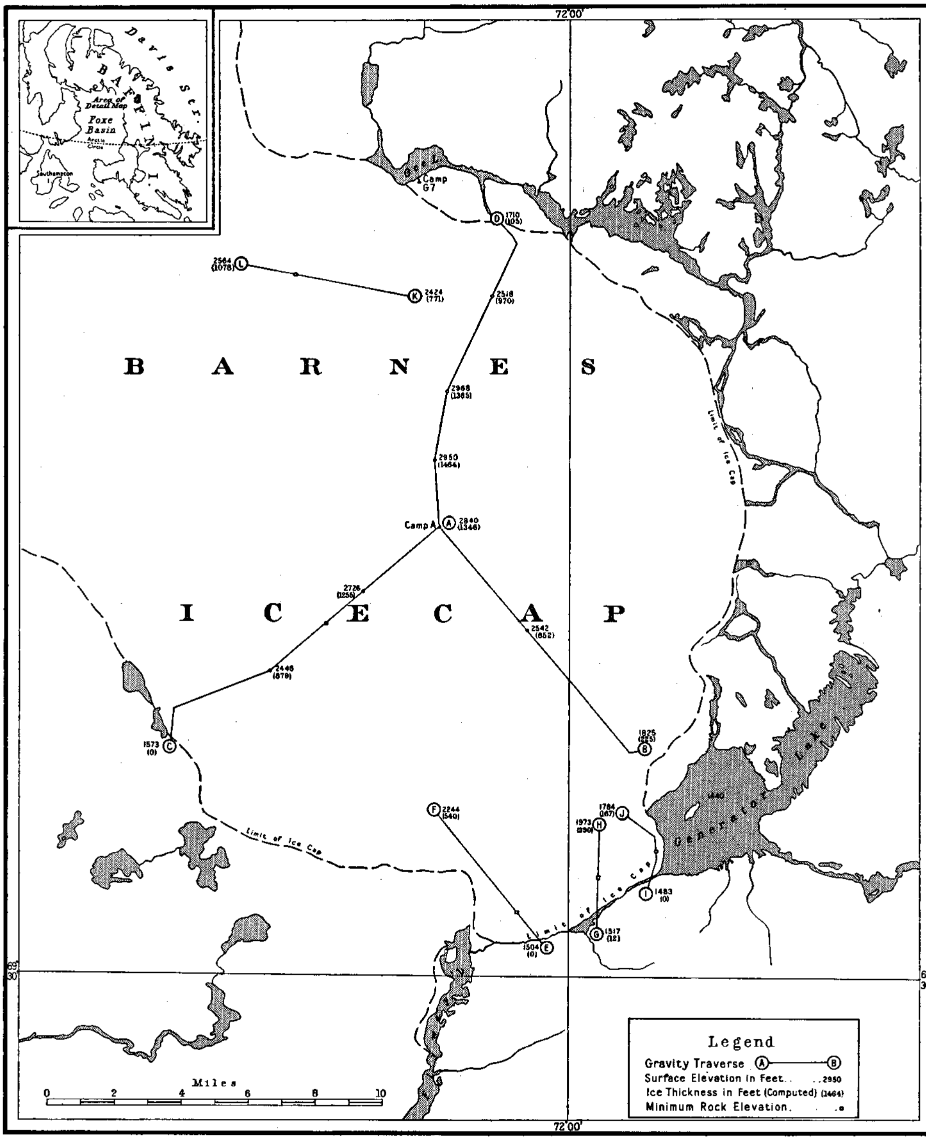

Fig. 1.

standard exploration instrument capable of measuring with precision small variations in gravity. This instrument was equipped with a high range reset mechanism which was controlled by a large dial calibrated in gravity units and could be used effectively for making long range gravity ties with no danger of the instrument going off-scale.

The constants of the instrument, as determined by tilt-table calibration and supplied by the manufacturer, are:

Large dial, 5.60 milligals per division.

Small dial, 0.10214 milligal per division.

A rough check on this calibration was made by reoccupying gravity stations established with pendulum apparatus at Goose Bay and at Frobisher Bay.[1] Comparison of the pendulum and gravimeter values is as follows:

	Pendulum	*Gravimeter*	*Difference*
Ottawa	980.622	980.6220	
Goose Bay	981.312	981.3164	+4.2 mg.
Frobisher Bay	982.167	982.1647	—2.3 mg.

The differences do not exceed the possible error of the pendulum determinations and since the measurements involve a large change in gravity, the calibration supplied by the manufacturer was accepted.

Drift of the instrument was determined on the basis of periodic repeat measurements at Camp A, whenever possible. However, because the long traverses required an absence from base for several days, an accurate drift curve for each day's operation could not be constructed. It was therefore necessary to adopt a mean drift for the instrument while in use, derived from the total drift and the overnight drift. Probably due to shock during transit over the more difficult traverses on the ice cap, a considerable amount of irregularity was noticed in the drift rate. This limited the relative accuracy of the adopted values of gravity for the stations to about 0.5 mg.

Reduction of observations and the accuracy of the method

The gravimeter method of determining the thickness of glacial ice was first used by Jean Martin[2] on the French Expedition to Greenland in 1948. It is based upon the assumption that the difference in the gravity anomaly for a station on the ice cap from the anomaly for some reference station situated at the outer limit of the ice, is due to a difference in the height of the rock floor above or below the level of the reference station. For if g_a is the observed value of gravity at the reference station, and g_b the observed value of gravity for a station on the ice cap, then

$$g_b - g_a = \Delta g = \Delta\gamma - K\Delta H + 2\pi G\,(\sigma_1 h_1 + \sigma_2 h_2)$$

where

$\Delta\gamma$ is the latitude correction based upon the International Gravity Formula. The correction is negative if the station is north of the reference point and positive if it is to the south.

σ_1=density of glacial ice (0.91 gm./cc.).

σ_2=density of rock (2.67 gm. cc.).

h_1=thickness of glacial ice.

h_2=height of the rock surface above or below the reference elevation.

$\Delta h = h_1 + h_2$=difference between the elevation of the field station and the elevation of the reference station where there is no ice or where the ice thickness can be measured by other methods.

K=free air correction factor= -0.09406 milligals per foot.

solving for h_2 gives

$$h_2 = \frac{\Delta g - \Delta\gamma + (K - 2\pi G\sigma_1)\,\Delta H}{2\pi G\,(\sigma_2 - \sigma_1)}$$

$$\text{or } h_2 = \frac{\text{Bouguer anomaly (using the density of ice)}}{2\pi G\,(\sigma_2 - \sigma_1)}$$

[1]Beer, M. "Measurements of gravity in the Canadian Arctic and Greenland". *Can. J. Res.* Vol. 28 (1950) pp. 535-41.

[2]Martin, J. "Gravimétrie" in 'Rapport préliminaire de la campagne préparatoire au Grœnland'. 5 Série Scientifique (1948) pp. 28-41.

If the Bouguer anomaly is positive, h_2 is positive and the rock elevation is greater than the reference elevation. The opposite is true if the anomaly is negative.

Before applying this formula to the results $\triangle g$ must be corrected for the departure of the topography near the gravity station from an infinite plane. With the available information this terrain correction could be assessed using standard methods to within 0.2 milligal. $\triangle g$ must also be corrected for regional changes in gravity due to both deep-seated effects and density changes in the near surface rock formations. There is no precise means of making this correction since the only information concerning the regional change is contained in the Bouguer anomalies for those stations established beyond the limit of the ice or for those for which the ice thickness is known by other methods. It is therefore necessary to assume that the gradient of gravity due to these causes is linear between the control points of the traverses. While such an assumption may produce little error in the shorter traverses, there may be large errors introduced in the longer ones. It has been found that changes in the density of surface rocks in other areas of the Precambrian Shield can produce gradients as much as six milligals per mile.

Assuming that the regional corrections are precise and that the densities used in the reductions are correct, 2.67 for rock and 0.91 for ice, an error of one milligal in the gravity anomaly produces an error of about 45 feet in the computed thickness of glacial ice. An error of one foot in the relative elevation of a gravity station produces an error of about 4 feet in the computed ice thickness. The combined errors in the determination of position, relative elevation, relative gravity, and terrain correction will not be greater than 0.8 milligal and should be usually smaller than this amount. The error in the computed ice thickness due to these causes should be within $\pm$ 35 feet.

Apart from these sources of error the gravity method at its best can but indicate the order of magnitude of ice thicknesses. This follows directly from the theory in which it is assumed for mathematical convenience that the rock surface beneath the ice approximates an infinite level sheet. Therefore the precision of the gravity method depends on how closely the rock surface does approach this condition. The precision also decreases with increasing ice thickness. For example, an increase in the gravity anomaly of 1 milligal is interpreted as indicating a general rise in the rock floor by about 45 feet. However, if the thickness of ice was approximately 1,200 feet, a rocky ridge 400 feet wide and rising about 400 feet directly below the gravity station would produce only the same gravity anomaly. From this it is apparent that gravity measurements alone cannot indicate such variations in the rock surface below ice thicknesses of this order.

Results and conclusions

Table 1 gives the principal facts for all regional stations including those established en route to and from Baffin Island. Stations designated by letters are end points of gravity traverses made over the ice cap as shown in Fig. 1. The Bouguer correction for all stations whether situated on the ice cap or not has been made assuming a density of 2.67 gm. per cc. The Bouguer

Station		Longitude		Latitude		Elevation, ft.	Theoretical gravity, γ_o	Corrections		Computed gravity		Observed gravity	Gravity anomalies	
No.	Name	°	′	°	′			Elevation	Bouguer	Free Air	Bouguer		Free Air	Bouguer
1	Goose Bay	60	25.6	53	19.2	131	981.3704	–0.012	–0.008	981.358	981.362	981.3164	–0.042	–0.046
2	Fort Chimo	68	24.5	58	06.0	105	.7723	– .010	– .006	.762	.766	.7276	– .034	– .038
3	Frobisher Bay	68	33.3	63	44.8	67	982.2056	– .006	– .004	982.200	982.202	982.1647	– .035	– .037
4*	Pond Inlet	77	59.6	72	41.7	10	.7618	– .001	– .001	.761	.761	.7251	– .036	– .036
5*	Arctic Bay	85	10.0	73	02.0	12	.7790	– .001	– .001	.778	.778	.7467	– .031	– .031
6*	Clyde	68	33.8	70	27.3	10	.6401	– .001	– .001	.639	.639	.6390	.000	.000
7		71	07.3	70	50.2	0	.6634	.000	.000	.663	.663	.6243	– .039	– .039
8		70	39.1	70	25.3	0	.6382	.000	.000	.638	.638	.5898	– .048	– .048
9		70	23.5	69	49.7	0	.6024	.000	.000	.602	.602	.5713	– .031	– .031
10		70	07.1	69	59.2	0	.6131	.000	.000	.613	.613	.5730	– .040	– .040
11		69	01.7	69	58.2	0	.6121	.000	.000	.612	.612	.5830	– .029	– .029
12	Camp G 7	72	11.1	69	50.6	1542	.6047	– .145	– .093	.460	.512	.4873	+ .027	– .025
A	Camp A	72	09.6	69	41.6	2840	.5959	– .267	– .170	.329	.426	.3674	+ .038	– .059
B		71	54.8	69	35.8	1825	.5902	– .172	– .110	.418	.480	.4458	+ .028	– .034
C		72	29.0	69	35.9	1573	.5903	– .148	– .094	.442	.496	.4647	+ .023	– .031
D		72	05.1	69	49.4	1710	.6036	– .161	– .103	.443	.501	.4742	+ .031	– .027
E		72	01.9	69	30.9	1504	.5854	– .142	– .090	.443	.495	.4704	+ .027	– .025
F		72	09.6	69	34.3	2244	.5887	– .211	– .135	.378	.454	.4129	+ .035	– .041
G		71	57.9	69	31.3	1517	.5858	– .143	– .091	.443	.495	.4712	+ .028	– .024
H		71	57.8	69	33.8	1973	.5882	– .186	– .118	.402	.470	.4337	+ .032	– .036
I		71	54.2	69	32.3	1483	.5867	– .140	– .089	.447	.498	.4747	+ .028	– .023
J		71	55.6	69	34.2	1784	.5886	– .168	– .107	.421	.482	.4504	+ .029	– .032
K		72	11.9	69	47.6	2424	.6018	– .228	– .145	.374	.457	.4140	+ .040	– .043
L		72	23.9	69	48.4	2564	.6026	– .241	– .154	.362	.449	.3994	+ .037	– .050

* These stations are located at astronomical monuments of the G.S.C.

Table 1. Principal facts for gravity stations.

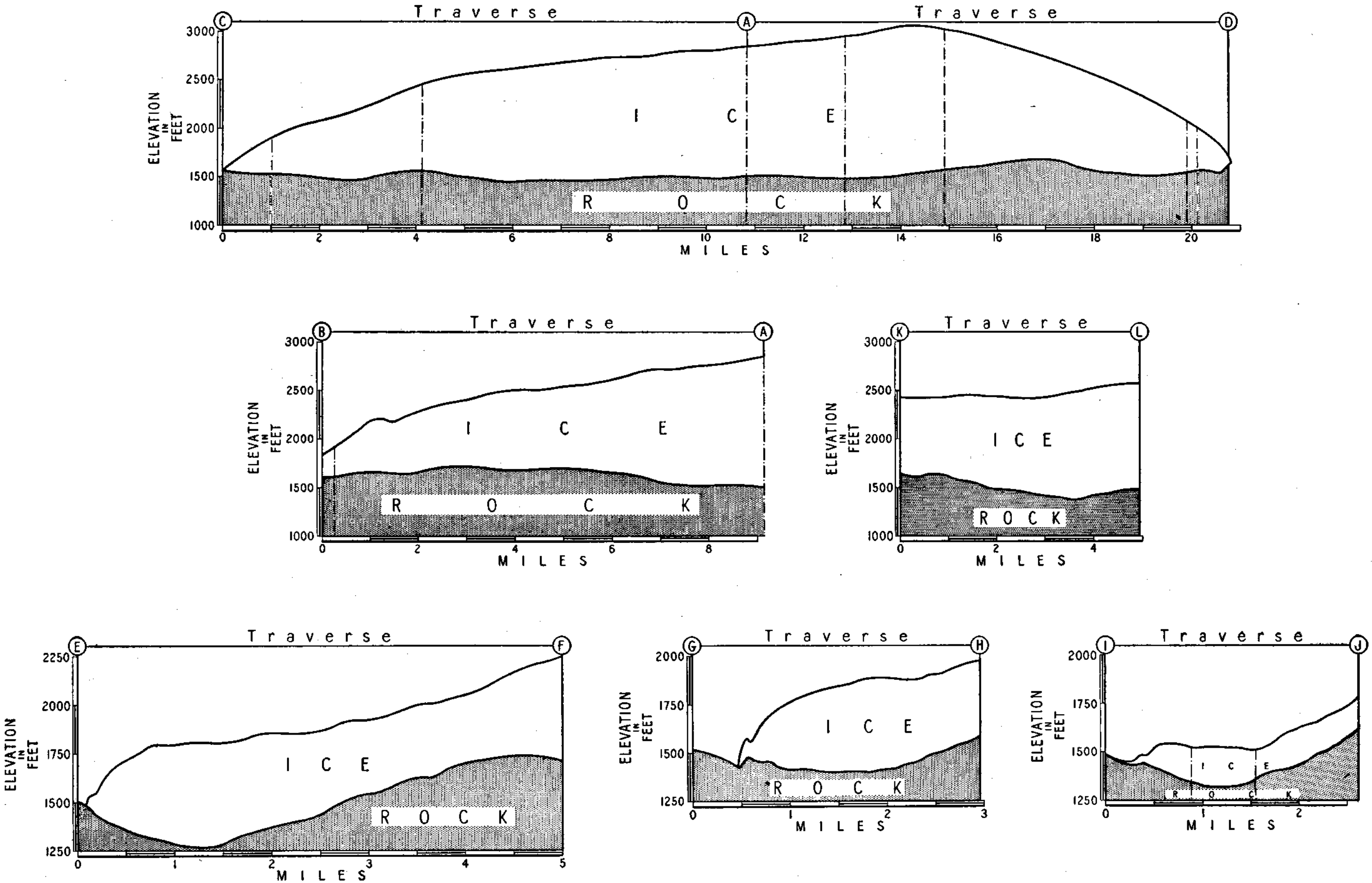

Fig. 2. Cross sections of the gravity traverses. The dotted lines indicate turning points.

anomalies for those stations beyond the limit of the ice were used to determine the regional correction.

The measured surface elevations and the computed rock elevations and ice thicknesses for the traverses are shown diagrammatically in Fig. 2. Table 2 gives these measurements and the differences in gravity corrected for terrain for traverse AB, selected as a typical traverse.[1]

Station	*Distance from reference station in miles*	*Observed gravity difference in milligals*	*Surface elevation in feet*	*Rock elevation in feet*	*Ice thickness in feet*
B–28	0.00	–18.52	1825	1600	225
27	0.59	–34.09	2026	1641	385
26	0.89	–43.83	2151	1653	498
25	1.48	–46.89	2192	1644	548
24	2.24	–55.37	2318	1684	634
23	2.93	–60.38	2391	1718	673
22	3.52	–66.82	2469	1696	772
21	4.38	–69.25	2506	1690	815
20	5.11	–71.57	2542	1690	852
19	5.86	–75.61	2591	1658	932
18	6.44	–81.57	2658	1619	1039
17	7.15	–87.01	2711	1540	1170
16	7.89	–90.30	2751	1516	1235
15	8.52	–92.97	2791	1517	1274
A–12	9.13	–97.00	2840	1494	1346

Table 2. Computed rock elevations and ice thicknesses along Traverse AB.

Considering first the longer traverses CAD and AB, the greatest ice thickness indicated by the results is 1,533 feet. This occurs near mile 14 on traverse CAD. For the reasons already mentioned, where ice of this thickness is found, abrupt changes in the computed rock elevations would not be expected. The greatest slope is along AD where the rock elevation changes about 60 feet in a distance of three-quarters of a mile. The results show that the floor of the ice cap near the middle of the lobe is on the average about 100 feet lower than it is near the margin.

Somewhat similar results are obtained for the shorter traverse KL. The indicated ice thickness averages roughly 1,000 feet, and there is a small depression of the rock floor reaching a minimum about mile 3.7.

The shorter traverses EF, GH, and IJ were surveyed to see if the results would confirm the existence of the subglacial valley which was suggested by the topography. The sections in Fig. 2 show that at about mile 1.3 along each traverse the rock elevations are 100 to 200 feet lower than the respective reference stations. The locations of the points of minimum rock elevation are given in Fig. 1 and their relative positions do suggest the course of a valley beneath the ice extending from Generator Lake to the northern end of Flyway Lake. Because of the greater density of gravity stations along these traverses and because the indicated ice thickness seldom exceeds 500 feet and is usually much less than this amount, there is a good possibility that the results are comparatively accurate. The indicated rise in the rock floor near mile 0.5 on both GH and IJ is most likely due to morainic material in the ice.

I wish to thank Mr. Hans Röthlisberger and Mr. Franz Elmiger of Switzerland and Mr. J. D. C. Waller of Montreal for their assistance in carrying out the survey. I am also indebted to various members of the staff of the Dominion Observatory for their help in the preparation of this report.

[1]These figures are available for all traverses at the Montreal Office of the Institute.