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A NEW FIELD EXPERIMENT IN THE GREENLAND ICE CAP TO TEST NEWTON'S INVERSE SQUARE LAW

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Abstract

A geophysical experiment was conducted in a 2-km-deep hole in the Greenland ice cap at depths between 213 m and 1673 m to test for possible violations of Newton's inverse-square law. A detailed ice-sounding radar survey was carried out to 5 km from the hole and merged with regional airborne radar data to define the basement interface. Highly accurate gravity measurements were carried out to 15 km from the hole to detect lateral density changes in the bedrock. The measurements were controlled with very accurate satellite and conventional positioning techniques. The basement interface model was input into a Newtonian computation to correct the observed gravity for known earth structure resulting in an anomalous gravity gradient of +3.87 mGal. A 3 dimensional ideal body analysis of the surface and borehole gravity data provided a means of bounding all possible Newtonian solutions for lateral density variation below the ice. Solutions with regional gravity offsets $\geq$ 10 mGal and density contrasts $\leq$ 0.30 g/cm^3 are possible. We cannot unambiguously attribute the anomalous gradient to a breakdown of Newtonian gravity because there remains the possibility it is due to unexpected geological features in the rock below the ice.

Recent experimental evidence suggests that Newton's law of gravity may not be precise (1,2). There are modern theories of quantum gravity that, in their attempts to unify gravity with other forces of nature, predict non-Newtonian gravitational forces that could have ranges on the order of 10^2-10^5 m. If they exist, these forces would be apparent as violations of Newton's inverse square law. A geophysical experiment was carried out to search for possible finite-range, non-Newtonian gravity over depths of 213-1673 m in the glacial ice of the Greenland ice cap. The principal reason for this choice of experimental site is that a hole drilled through the ice cap already existed, and the uniformity of the ice eliminates one of the major sources of uncertainty arising in the first of earlier studies[2], namely, the heterogeneity of the rocks through which a mineshaft or drill hole passes. Our observations were made in the summer of 1987 at Dye 3, Greenland, in the 2033 m deep borehole, which reached the basement rock. The site is 60 km south of the Arctic Circle, 125 km inland from Greenland's east coast, and at 2560 m elevation (Fig. 1).

The general configuration of the experiment is presented in Figure 2. The Newtonian prediction of the gravity profile in the borehole, based on a density model of the ice and the topographic relief of the bedrock and ice surface developed from geophysical measurements, was compared with measured values. Differences in gravity, g, were measured at several depths, z, and modeled by:

$$g_m(z) \approx \gamma z - 4\pi G\rho_i z + g_r(z), \tag{1}$$

where γ is the theoretical free-air gravity gradient, G is the Newtonian gravitational constant as determined in laboratory experiments, ρ_i is the ice density, and g_r is a correction to the gravity differences based on the attraction of the sub-ice terrain. (The effect of the ice-surface topography is negligible.) Although Eq. (1) is adequate within the uncertainties of our experiment, a more exact expression[4] which accounts for a vertical change in density, and the earth's ellipticity was used in the calculations. The gravity anomaly, g_{anom}, is defined as the difference between the modeled gravity, g_m, and the observed gravity in the borehole, g_{obs},

$$g_{anom} = g_{obs}(z) - g_m(z). \tag{2}$$

The steps taken to obtain the experimental observations and model calculations will be described. The results are shown in Table 1. The uncertainties in this table include contributions from the measurements themselves and from imperfect knowledge of the ice density and the terrain, with the latter effect dominating. They do not reflect an ignorance of the density inhomogeneities in the underlying rock.

An accuracy of one part in one thousand was determined to be necessary in all measurements in order to provide the gravity sufficiently accurately to detect the theoretically predicted deviations in Newtonian gravity. This would require not only accurate gravity measurements but also accurate locations of all observations, because of the effect of variation of gravity with location, especially elevation.

In order to insure an ultimate accuracy of less than 0.03 mGal, the borehole gravity meter was calibrated in Canada and Alaska over the range of gravity values expected in the Dye 3 borehole by comparison with the readings of an absolute gravity meter[5], resulting in uncertainties in calibration less than 0.03 mGal in the borehole.

The borehole in Greenland is not vertical, so its trajectory was obtained from downhole inclinometers. The wireline to be used for lowering the gravimeter down the hole, was calibrated in a 1520 m mine shaft at the Consolidated Silver mine in Idaho by comparison with a laser geodimeter[5] before and after the Greenland experiments and resulted in measured depths to an accuracy of about 1 part in 10^4.

Approximately 100 gravity observations were made in the borehole distributed over 8 stations placed at 183 m intervals. The uncertainty in the gravity measurement at each depth is estimated to be 0.05 mGal. A surface gravity survey was performed with LaCoste-Romberg relative gravity meters. The region covered was 32 km in diameter and consisted of 25 sites on three rings and at the center. Each site was occupied four times (variously by two different observers) with four gravity meters. Elevations for the sites were obtained with a combination of first-order optical leveling and satellite observations with the Global Positioning System. After corrections (to be described below) the gravity values are used to provide further constraints on possible sub-ice density variations.

The properties of ice have been extensively studied; samples from Dye 3 have been analyzed in detail[6] and densities were calculated to an accuracy to 7 parts in 10^4 over the depth range of our experiment[5].

Additional gravity gradients are created by the undulations of the basement rock; it is therefore important to map the ice thickness for a considerable distance around the site of the experiment. Airborne and ground ice-penetrating radar surveys had previously been made in the vicinity of the site[7], providing moderately accurate coverage to a distance of more than 60 km. A more detailed surface radar survey was completed within a 5 km radius of the Dye site using the Scott Polar Research Institute radar system[5] (Fig. 3). The bedrock topography map was constructed from the radar travel-times by a three-dimensional migration algorithm (recorded along 124 radial lines for a total of about 42,000 soundings). The resultant map is defined by a grid at a 125 m interval with a vertical uncertainty of $\leq$ 5 m over 70% of the area. In a few exceptional places far from the borehole, where reflections were very weak, the uncertainty rose to 50 m. Ice thickness estimates range, with position, from approximately 1800 m to 2100 m and is in general agreement with previous regional surveys. The ice surface topography was also mapped, out to 5 km from the borehole, to an accuracy of about 1 m using an electronic distance meter and theodolite.

The gravitational effect of bedrock topography (the terrain correction) was computed at each gravity observation point, both on the ice surface and in the borehole, using two different techniques. The bedrock density was taken as 2.70 g/cm^3, as given by Jezek et al.[8]. The two calculations agreed to within 0.01 mGal at locations down the hole. Imperfect knowledge of the terrain was the largest component of the gravity corrections.

After all these conventional adjustments are applied, there remains an unexplained gravity difference of 3.87 ± 0.36 mGal between the gravity value at a depth of 213 m and at 1673 m.

The rock beneath the ice has been treated as homogeneous. However, density variations in the rock generally produce vertical gravity gradients and geological studies of the coastal regions of Greenland show that mafic intrusions with densities from 2.8 to 3.0 g/cm^3 are found within the metamorphic basement and occupy a few percent of the exposed basement rock[9]. The surface gravity map (Fig. 4) reveals anomalies within our network that could be due to such masses.

To demonstrate unambiguously the inadequacy of a purely Newtonian explanation, one must show that no reasonable density variation in the basement can produce the observed anomalous borehole gravity profile without conflicting with the surface gravity survey data. It is well known that even complete gravity information outside a body cannot uniquely determine the internal density structure. However, the theory of ideal bodies[10] leads to a rigorous calculation of the smallest possible density contrast mathematically consistent with a finite number of gravity observations. If such a calculation showed that a geologically unacceptable density contrast was required to produce the measure gravity values, the case for a modification of Newton's law of gravity would be made.

The smallest density contrast was found subject to a specified weighted sum of the squared misfit to the observations and their associated errors. All 25 surface values and 8 borehole values were used. The problem was solved approximately with a quadratic programming algorithm, which constructs a block model of the density distribution. It is easily shown that the density contrast causing the Chi squared-per-degree-of-freedom value to achieve a specified value is the smallest possible density contrast consistent with that misfit. Thus, by varying the density we can find the least density contrast within the basement necessary to reproduce the observations as measured by the size of the misfit functional.

All the gravity measurements are relative, so that, in principle the same arbitrary constant may be added to each one.

To avoid the necessity of huge anomalous masses whose presence would be inconsistent with geological considerations, an offset is allowed as a parameter in the fit. Since the gravity survey reveals variations in the corrected surface gravity of up to 10 mGal, values on this order for the arbitrary constant are acceptable, but values several times larger would be difficult to justify.

The bound on the density contrast and the constant gravity offset was systematically varied and the results displayed as the smallest possible misfit to the observations. The squared misfits were normalized by the number of observations (Chi-squared-per-degree-of-freedom, see Fig.5). The unit contour line defines a good fit to the data, and a good fit can be obtained for large but plausible density contrasts and acceptable offset values. For example, the mass distribution depicted in Figure 6, generated by the ideal-body code, has a density contrast of 0.3 gm/cm^3 (larger than this may be geologically unreasonable for Greenland) and a regional offset of 10 mGal. The mass distribution simultaneously fits the surface and borehole gravity observations. The intrusive bodies represent a larger amount of mass than would be expected based on geologic maps of the Greenland coast, where the rock is exposed[9]. Further, these bodies fit the surface data alone and need only slight alteration to fit the borehole data as well.

The distribution found is not meant to be interpreted as the actual one in the earth. It is representative of mathematically possible solutions for the density lower bound. The fundamental nonuniqueness of the inverse gravimetric problem makes it impossible to identify the actual density distributions responsible for the gravity observations.

The above indicates that any complete analysis of geophysical experiments searching for non-Newtonian gravity should include a careful estimate of the ability of small density contrasts to generate substantial vertical gravity gradients. Future experiments should be designed with this approach in order to quantify the gravitational contribution of geologic heterogeneity. The best experiment will be one in which the anomalous gravity demonstrably exceeds the quantifiable geologic "noise".

In conclusion, an anomalous gravity gradient was found that could be taken as evidence for non-Newtonian gravity. This possibility was tested by using regional gravity offset and density contrast as parameters in an ideal-body analysis, which found that the data can be fit with a Newtonian gravity model if one allows large mafic intrusions in the bedrock and a significant regional gravity offset. These findings could be further tested by performing other geophysical surveys in the region, such as aeromagnetic, to define the extent of the intrusives.

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TABLE 1

z	Δz	$\gamma\Delta z$	g_{ice}	g_r	g_m	g_{obs}	$g_{obs}-g_m$	σ_g
212.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.26
396.12	182.90	56.37	-14.06	-0.25	42.06	42.39	0.33	0.25
579.00	365.78	112.74	-28.13	-0.52	84.06	84.72	0.63	0.23
761.83	547.61	169.09	-42.21	-0.82	126.06	127.13	1.07	0.20
944.63	731.41	225.45	-56.31	-1.14	168.00	169.48	1.48	0.19
1309.40	1096.18	337.91	-84.44	-1.92	251.55	254.10	2.55	0.15
1491.18	1277.96	393.97	-98.47	-2.40	293.10	296.32	3.22	0.13
1673.23	1460.01	450.11	-112.52	-2.95	334.64	338.51	3.87	0.25

Table 1. This contains the absolute observation depths, z; the depths relative to the shallowest observation point, Δz; the theoretical free-air term, $\gamma\Delta z$; the effect due to the ice (approximately the second term in Eq. (1)), g_{ice}; the attraction of the sub-ice terrain, g_r; the theoretical gravity differences, $g_m = \gamma\Delta z + g_{ice} + g_r$; the observed gravity differences, g_{obs}; the anomalies, $g_{obs}-g_m$; and the uncertainties, σ_g. (Note: 1 mGal = 10^{-3} cm/s^2.) The modeled and observed values are offset to make them both zero at z = 213.22 m, which is permitted since all the gravity observations are relative. All distances are in meters and all gravity values are in mGal.

FIGURE CAPTIONS

Fig. 1. Location of Greenland Experiment at Dye-3 Distant Early Warning Radar Station.

Fig. 2. Diagramatic model of the earth at the Dye-3 well site. Approximate values of depths and densities are shown.

Fig. 3. 3 Dimensional view of detailed basement topography from radar soundings at Dye-3.

Fig. 4. Complete Bouguer gravity anomaly map of the vicinity surrounding the Dye-3 study area (which is located at 0,0).

Fig. 5. A contour map of $\chi^2/(33)$ obtained by fitting the 33 gravity station measurements with an ideal body of density contrast $\Delta\rho$ located at and below the rock-ice interface, in a field with regional gravity offset, Δg_0. The specific case of $\Delta\rho = 0.30 g/cm^3$ and $\Delta g_0 = 10$ mGal is exhibited in Fig. 2.

Fig. 6. The plan view, at the rock-ice interface, of the ideal body with density contrast $\Delta\rho = 0.30\ g/cm^3$, in a regional offset field of $\Delta g_0 = 10$ mGal, which can model the gravity observations. The vertical dimension of each piece of the ideal body is roughly the same as its horizontal dimension. The triangles denote the locations of the gravity measurements on the surface.

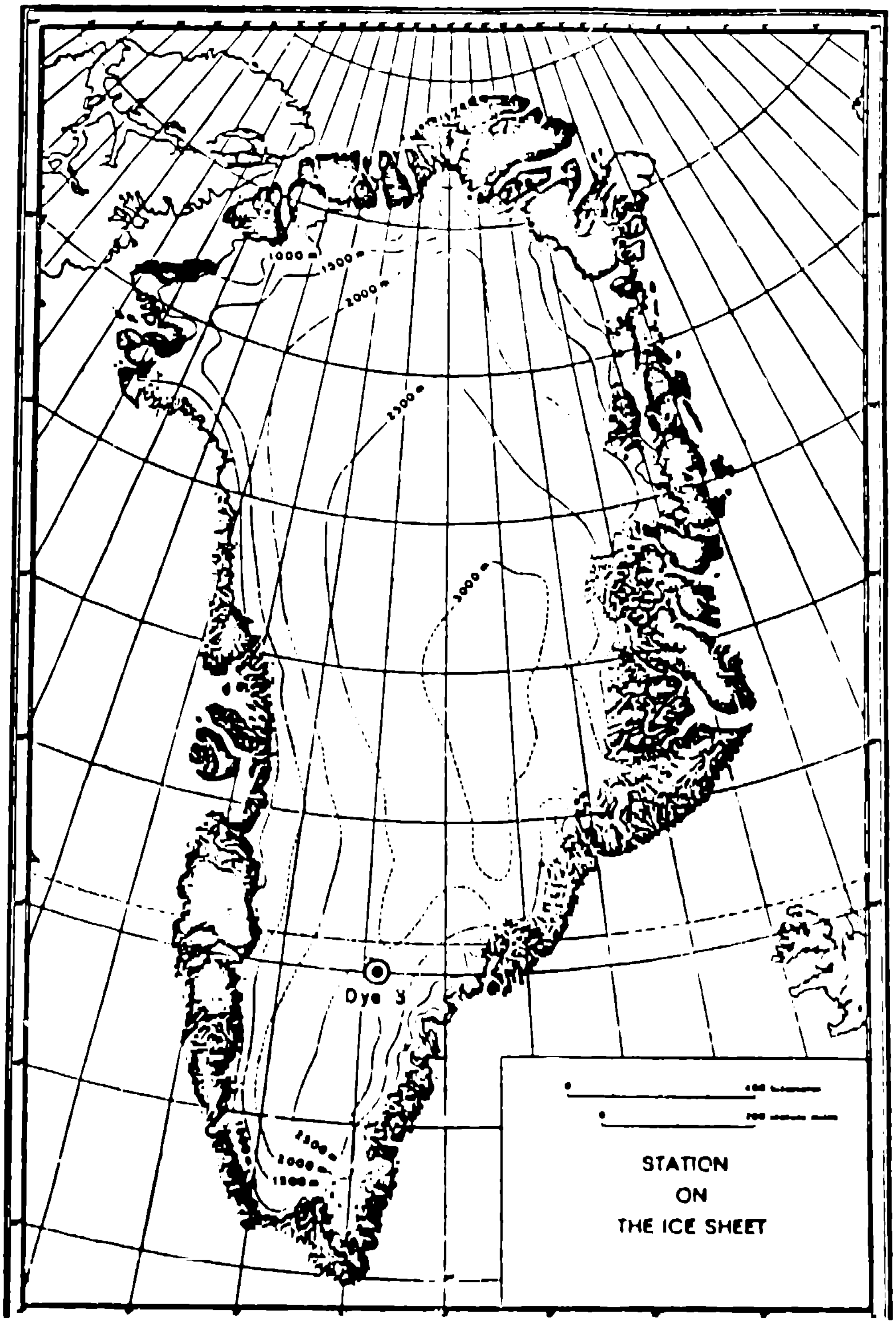
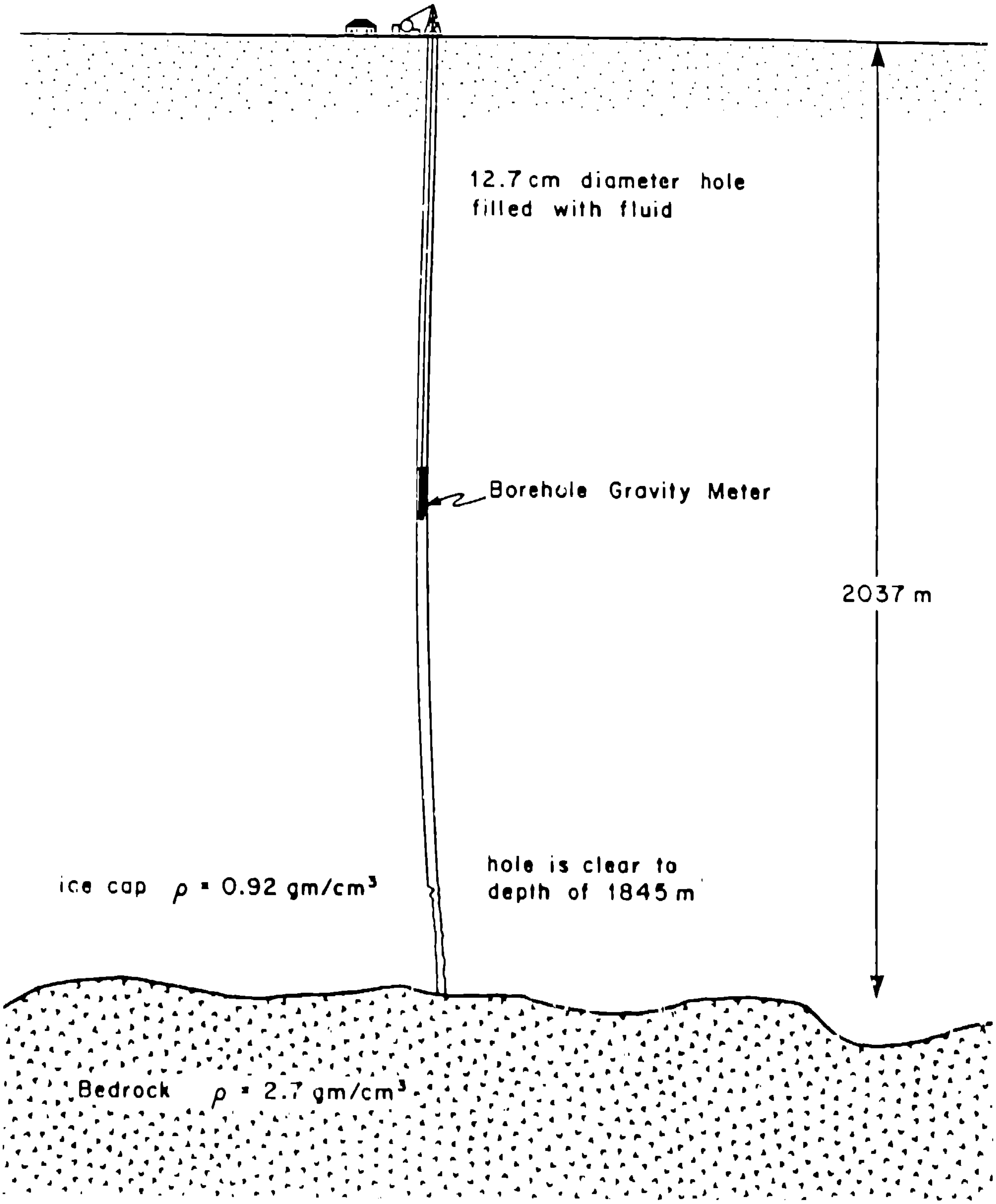
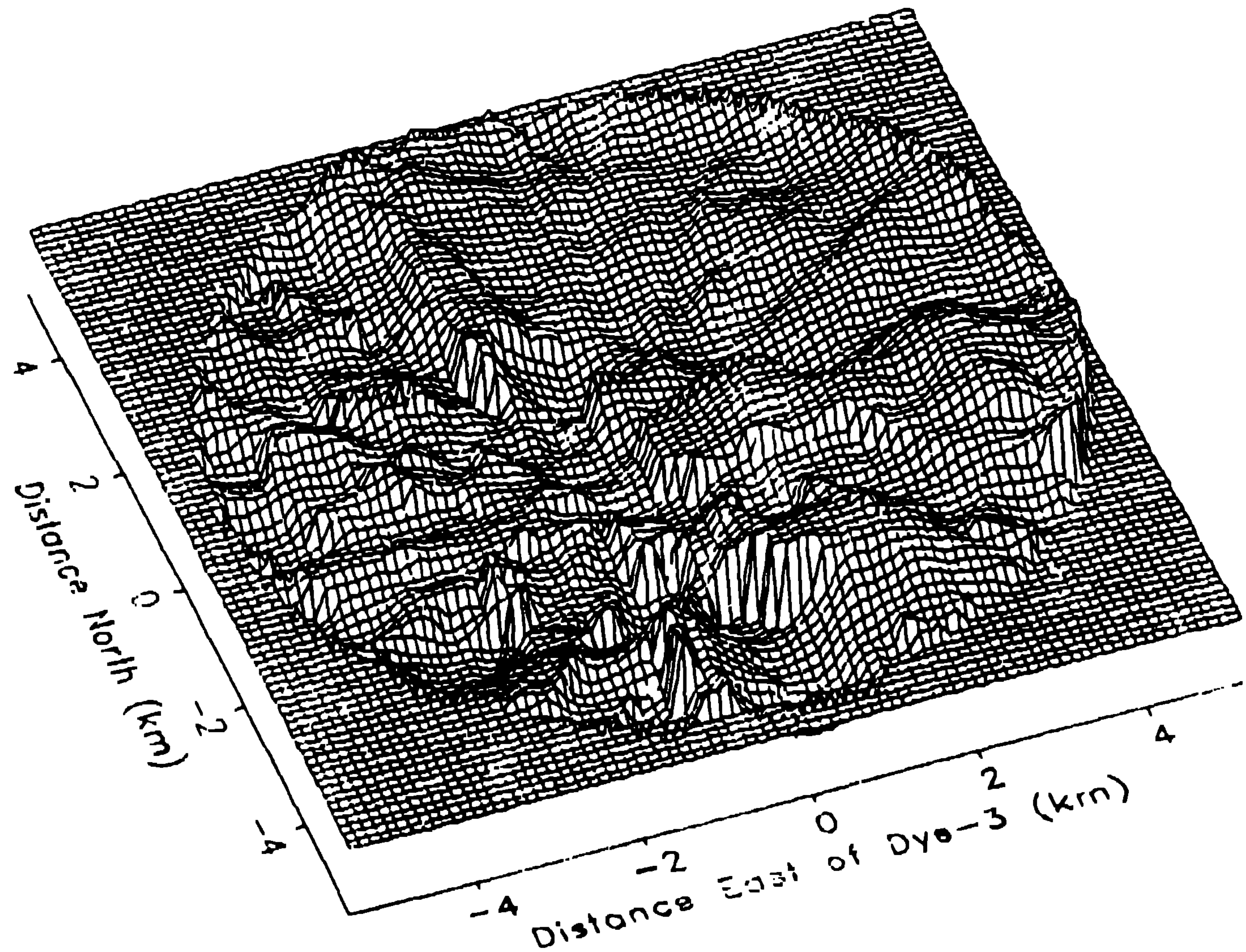


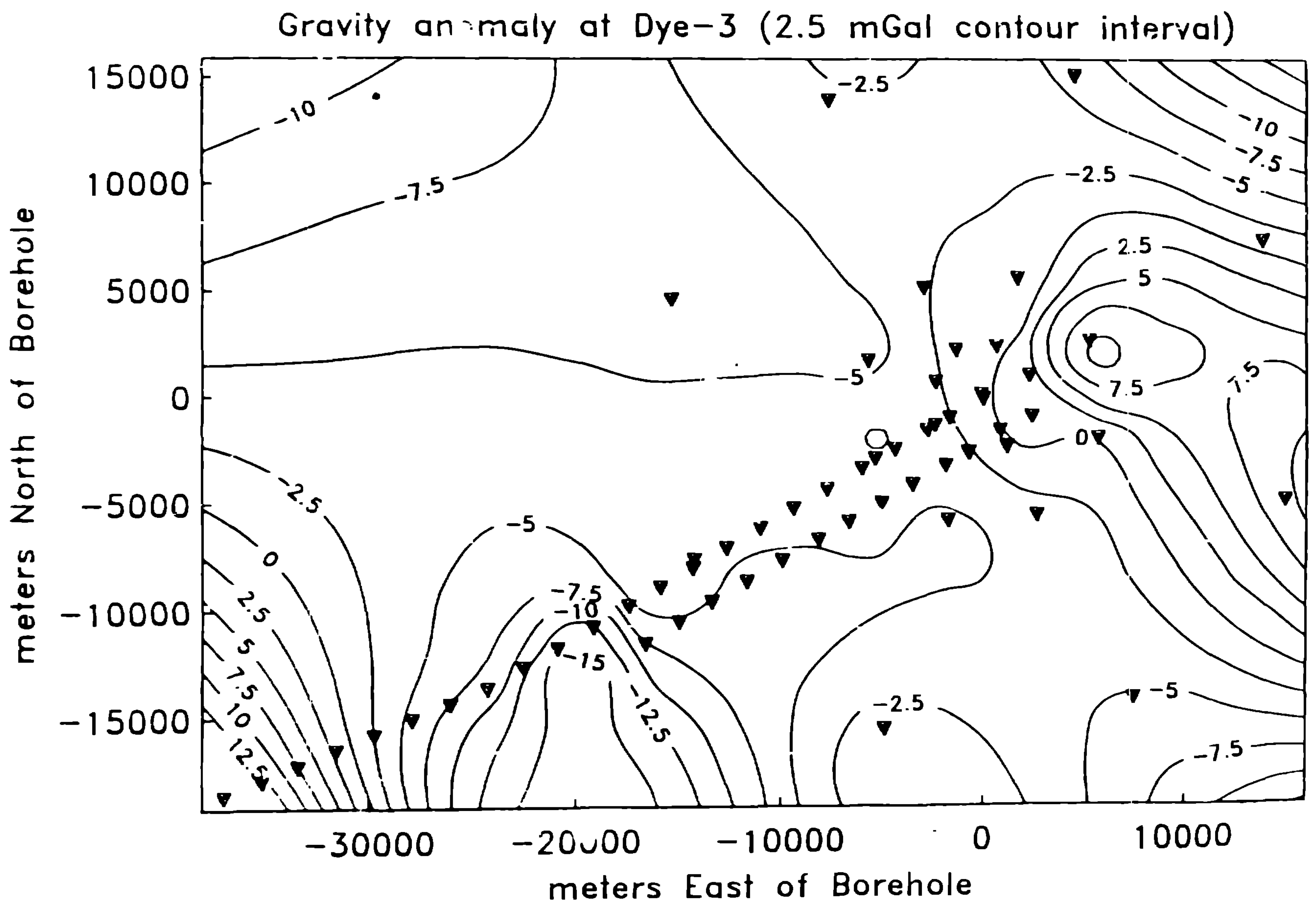
Figure 1

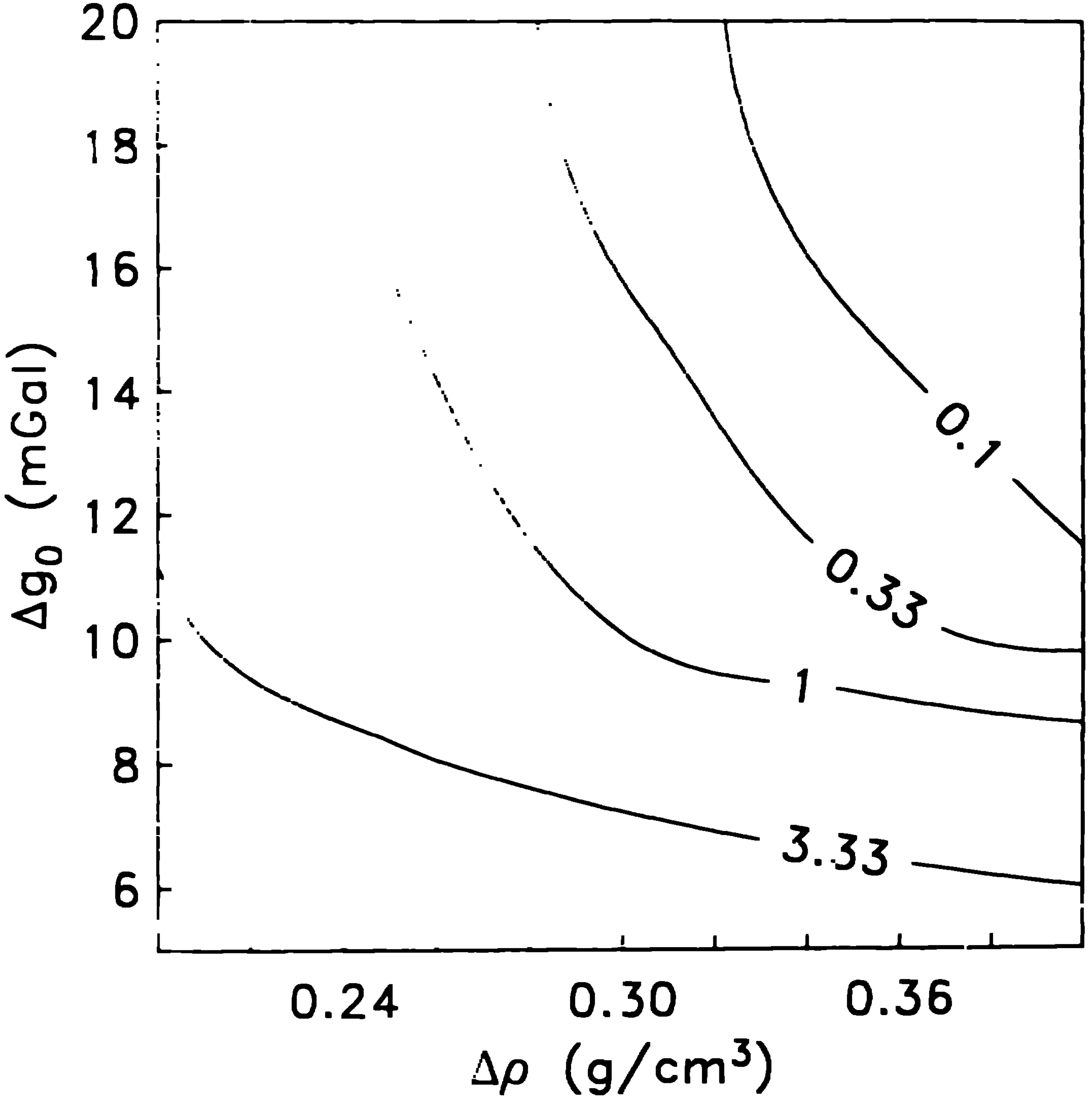
Dye 3, Greenland



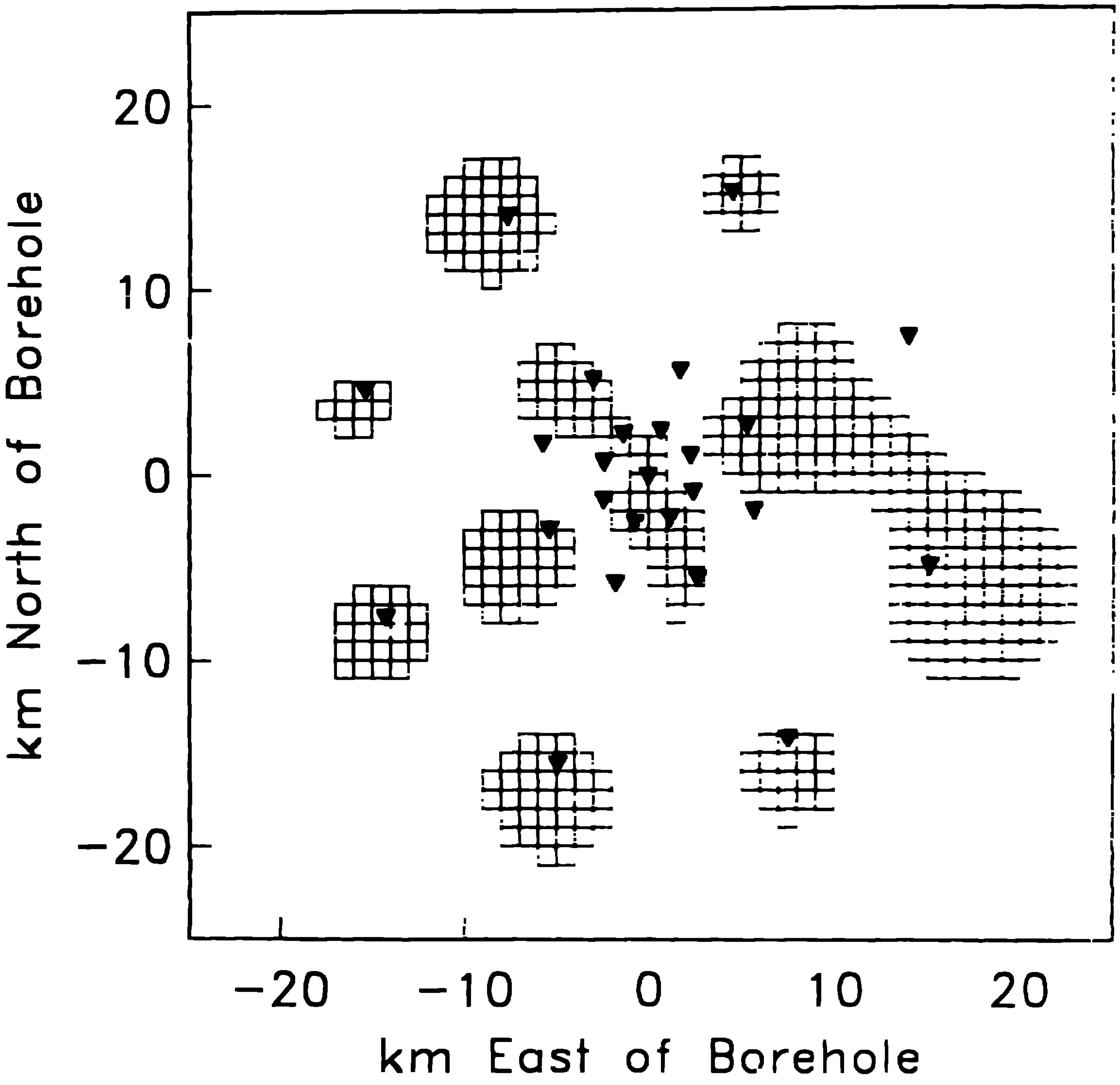
Elevation of basement about mean depth of 2004.11




Gravity anomaly at Dye-3 (2.5 mGal contour interval)
meters North of Borehole
meters East of Borehole
15000
10000
5000
0
-5000
-10000
-15000
-30000
-20000
-10000
0
10000
-10
-7.5
-5
-2.5
0
2.5
5
7.5
10
12.5
-12.5
-15



20
18
16
14
12
10
8
6
Δg_0 (mGal)
0.24
0.30
0.36
$\Delta\rho$ (g/cm^3)
0.1
0.33
1
3.33


20
10
0
−10
−20
km North of Borehole
−20
−10
0
10
20
km East of Borehole