SVERIGES GEOLOGISKA UNDERSÖKNING

SERIE C NR 746 AVHANDLINGAR OCH UPPSATSER ÅRSBOK 72 NR 8

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## INTRODUCTION

During the 1960's gravity measurements became of increasing importance as a prospecting tool in the so-called "järnmalmsinventeringen", i.e. iron ore exploration in the Norrbotten county of Sweden. Although the number of measurements sometimes amounted to 1 000 points/km$^2$, the measured areas were often of considerable size. This in turn led to a regional analysis of the gravity data, and the gravity survey has become of interest even on a larger scale.

The need for regional gravity measurements as well as the requirements regarding point density and accuracy will now be considered in greater detail.

1. When accurate separation of local and regional anomalies is desired the following requirements are suggested: a pointdistance of 100 m and an accuracy of 0.02–0.03 mgal nearest to the local anomaly, whereas the point distance is allowed to increase to 1 000 m and the accuracy to decrease to 0.2–0.3 mgal further away from the anomaly.

2. An important application of gravity surveys also to be mentioned is their usefulness in the search for relatively deep-seated ores and in the delineation of those shallowlying ore-types which cannot be detected by other geophysical methods. Point-distance and accuracy near the bodies are recommended to be in the order of 200 m and 0.02–0.03 mgal respectively, increasing to 500 m and 0.1 mgal at greater distances.

3. A gravity survey is a very useful aid to other geophysical methods, thereby providing a different set of parameters for more complete solutions of subsurface problems in general. It greatly supports the geological mapping, which at the moment is carried out on scales from 1:20 000 to 1:250 000. The point density

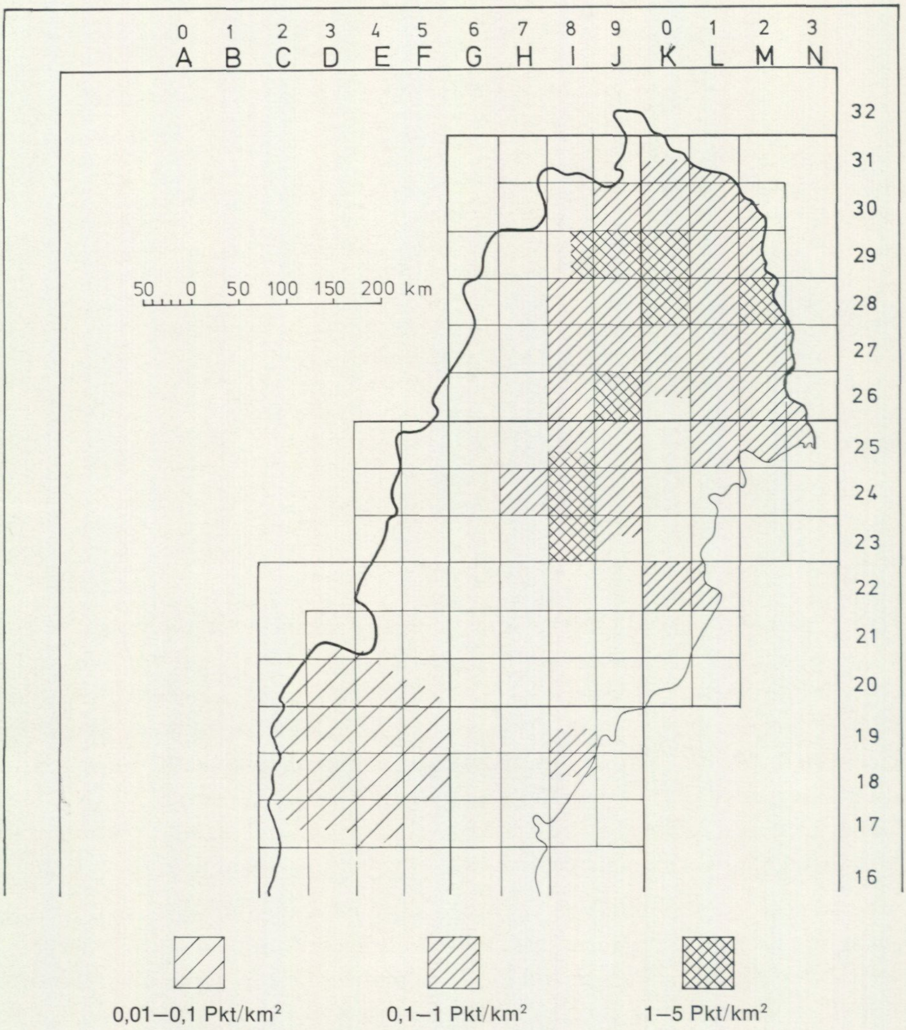


Fig. 1. 'Regional' and 'sub-regional' gravity measurements in Northern Sweden, January 1978.

and the accuracy of the measurements are highly variable parameters, whose values depend on the specific circumstances of the problem considered.

The gravity measurements carried out by *Rikets Allmänna Kartverk* (RAK, now included in *Statens Lantmäteriverk)* in northern Sweden, have a point density of 1 point per 100–1 000 km² (Wideland 1951 and Petterson 1967). This gravity network is thus too coarse to be used for our purpose. The measurements made by SGU have, however, been related to the already existing registrations. The regional gravimetric measurements made by SGU up to date are shown in Fig. 1. In the counties of Norrbotten and Västerbotten an area of 76 000 km² has been covered, while an area of 30 000 km² has been measured in Jämtland. Moreover, a small area of 2 000 km² on the Nordingrå coast in Västernorrland county should be mentioned. These regional measurements have quite different characteristics from place to place depending on the various purposes for which they were carried out. Our aim, however, is to publish standardized maps on the scale of 1:50 000 over areas including actual ore provinces, and to cover the whole country with maps on the scale of 1:250 000 in accordance with the map scales and divisions used by Lantmäteriverket (Fig. 1).

A bouguer gravity map (1:50 000) over 28 M Pajala has been published. The map 554 Huuki, on a scale of 1:250 000 (including 29 M Huuki and 30 M Muonionalusta), is in preparation. Moreover some gravity maps of the northernmost part of the country are prepared.

The gravity maps have already led to new theories of the geological picture of some areas, while older theories have been revised. The importance of these maps thus seems to justify a description of the technique behind the measurements, and their treatment.

## THE SEARCH FOR IRON ORE

The aim of the iron ore exploration in northern Sweden was primarily to map all iron ore deposits in this part of the country, viz. the already but insufficiently known ones as well as the undiscovered ones. In order to fulfil this task an organisation consisting of geologists, geophysicists, technicians, field operators, and drilling staff was set up.

The exploration was made on a grid net of 50×50 km. First of all an aeromagnetic survey was carried out. The mean flight altitude was 30 m, and the distance between flight traverses was 200 m. Areas interesting from an ore prospecting point of view were also investigated by means of detailed geological mapping and boulder tracing. It should be mentioned here that the character of the geological work has changed over the years and is now of a more general character. When the aeromagnetic map showed interesting anomalies and when it could be geologically supported, ground geophysical surveys, mainly magnetic and gravimetric measurements, were carried out.

The gravity measurements are related to the general gravity system made by RAK. Point altitudes are derived by means of levelling from spot heights. During correction of the field data, these are fitted to the existing absolute gravity system. All ground surveys include gravity measurements, because qualitative calculations can be made on more reliable data than in the case when working with magnetic data. The latter may be influenced by peculiar susceptibilities (Leveäniemi), ores containing hematite (Pattok), etc.

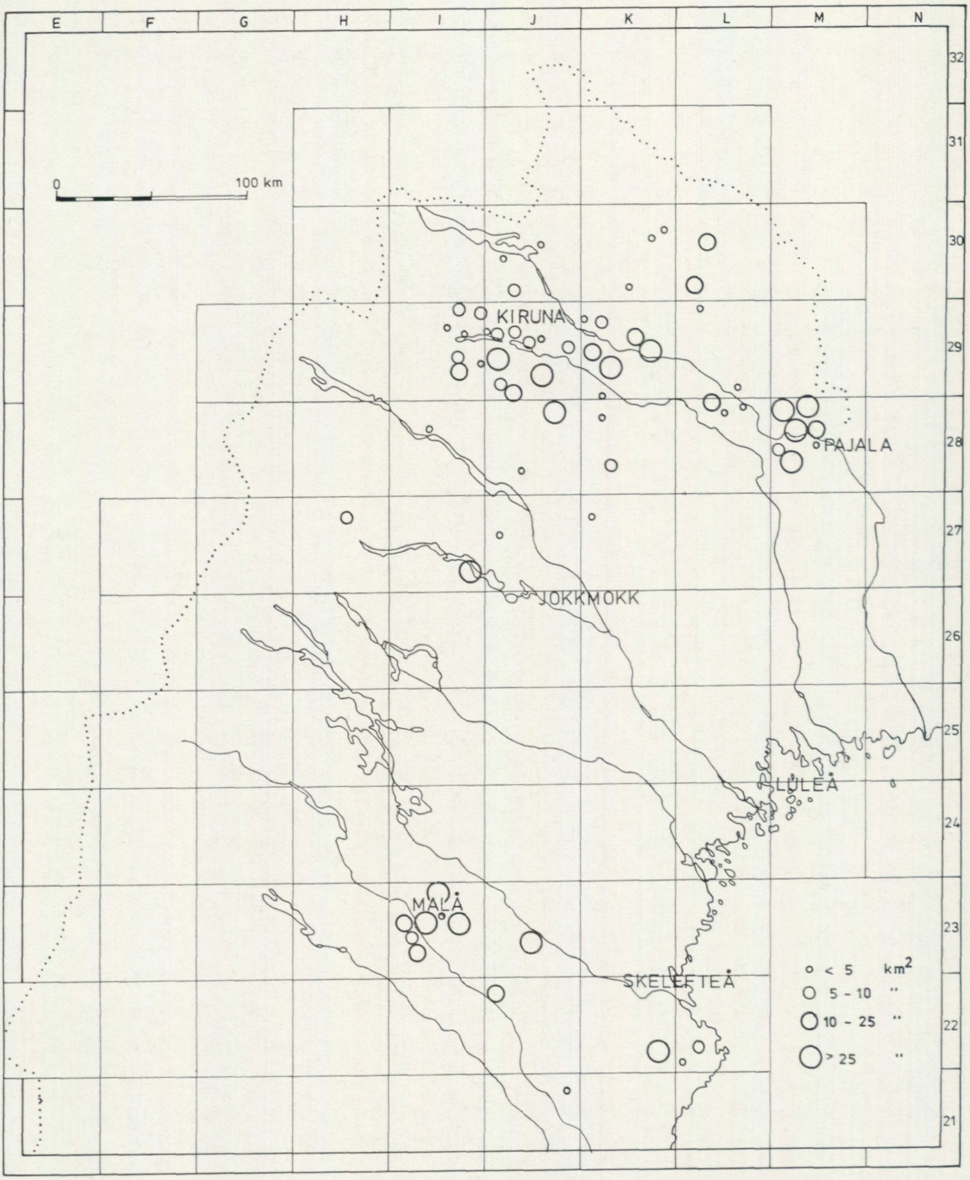


Fig. 2. Areas where detailed gravity measurements have been carried out by SGU.

The most disencouraging problem when dealing with gravity measurements is the separation of residual anomalies from regional anomalies, especially as the separation happens to be a fundamental step on the way to providing estimations of the volume of an ore body. Extensive radial measurements are therefore made in order to get a better idea of the regional behaviour of the gravity field.

These radial systems often cover rather large areas in the vicinity of the interesting objects.

The iron ore exploration was initiated on map 29 J Kiruna. Most effort was concentrated on this map as well as on the maps 29 I Kebnekaise, 29 K Vittangi and 28 M Pajala. The ground surveys made by SGU at that time are shown in Fig. 2. It should also be mentioned that even in the Kiruna and Malmberget areas measurements were carried out simultaneously by AB Elektrisk Malmletning (ABEM) under contract to the LKAB Company.

## ”REGIONAL” AND ”SUB-REGIONAL” GRAVITY MEASUREMENTS

The distinction between ’regional’ and ’sub-regional’ may sound peculiar, but it clarifies the meaning of the generally used term ”regional”. It appears to us, who have been working within prospecting for a long time, that such a distinction is of practical interest.

The point density of the regional measurements is roughly 1 point/km$^2$, and the points are equally spaced to a certain degree. The measurements in the Kiruna-Gällivare-Pajala ore belt belong to this category. Most of the registrations on the maps 26 J Jokkmokk, 24 I Storavan and 23 I Malå should also be classified as belonging to this group.

The sub-regional type of measurements, on the other hand, include measurements performed along roads or on certain profiles. The point distance is often less than 1 km. However the number of points per map-sheet is generally less in the case of sub-regional gravity surveys. This can be exemplified by the measurements in Norrbotten and Västerbotten counties with a point density in the order of 0.2–0.4 points/km$^2$, whereas in Jämtland county a point density of 0.03–0.07 points/km$^2$ is normal.

The regional gravity maps are produced on a scale of 1:50 000. Together with the sub-regional maps they will also become available in the 1:250 000 series.

## ALTITUDE DETERMINATIONS

As mentioned earlier in this paper, the regional gravity measurements were first employed in connection with the iron ore exploration on map 29 J Kiruna. It seems justified therefore to take a closer look at the experience gained from the work in this particular area. It is also important to note the topography of the Kiruna district with low, undulating terrain to the east and rocky terrain to the west.

A number of points with known altitude above sea level are found lying only a few kilometers apart along the very few roads and on the railway running from the south to the northwest. At a considerable number of these points gravity measurements have been carried out by RAK. Our regional programme began with a completion of the already existing lines, i.e. along the roads and along the railway. The point distance was set to about 200 m and point altitude were determined the usual way. The road measurements became a framework for the regional gravity survey together with the areas covered by detailed gravity surveys. This way of building up a gravity framework has also been used in most of the later work.

In the areas without roads, one of the main problems is how to measure altitude at moderate costs. The material available for 29 J Kiruna consists of a topographic map on the scale of 1:100 000 with contours at 10 m intervals. First outline maps on the scale of 1:20 000 are available as well as air photos on roughly the same scale. A satisfactory point identification has been obtained by using the photos and topographic maps in combination. In those cases where point choices were localized to well determined water surfaces, acceptable altitude determinations were obtainable. The rather elongated lake system of this particular area was used to a great extent for such purpose. Often the actual altitude of the water surface was found by means of fixed points already measured by the Swedish Meteorologic-Hydrographic Institute (SMHI) or the Swedish State Power Board.

On the Kiruna map-sheet, different experiments were carried out in order to find a suitable system for measuring altitude, and some of the results obtained will now be presented.

An obviously reasonable method, from an economic point of view, was the use of altimeters. During the summer of 1965, measurements with Paulin barometers were carried out in different parts of the map-sheet. Considerable effort was laid down to increase the precision. Two field crews each supplied with two barometers made simultaneous measurements by means of radio communication. Relative calibrations of the barometers were carried out step-wise during operation hours, while the absolute calibrations were carried out twice a day against a high precision mercury barometer.

To obtain a correction factor for the air-humidity changes a hygrometer was read at each station. Finally, because it is considered that temperature changes in the air column cause significant deviations in the final results, the temperature was registered at every point, thus allowing proper temperature corrections of the barometer readings to be made. The most important reasons for temperature differences in the lower atmosphere (0–500 m) are heat radiation changes from place to place which in turn give rise to air turbulence. These variations depend on the general weather situation, altitude and other, local factors. The best results were obtained on days of weak incoming heat radiation and practically no wind. Measurements were concentrated to these days, producing an average error of ± 1 m as the best result. This error does not include possible non-linear drift corrections, neither does it include the mean reading deviation. Considering the reading and calibration errors, which for a high precision Paulin instrument amount to at least 1 m, it seems impossible to get an average error on the results of less than 2 m.

The conclusion has been, that altitude measurements by means of barometers are neither a simple nor a cheap method.

The next step was to try to evaluate the heights by means of photogrammetry. The accuracy here depends mainly on the scale of the photo and the number of known reference heights on the photo. A test-determination of about twenty already known station altitudes gave an average error of 0.8 m in areas of moderate relief energy. In areas of high relief, i.e. the westernmost mountains, a decidedly higher mean error is registered. However, if the stations are chosen in favourable areas of low to moderate relief the average error can be kept below ± 2 m. The costs of this method are connected with the mounting of the stereo model, whereas the number of measurements on each photo is of minor importance. This method is therefore faster, cheaper and more practical for field work. Several station altitudes have been determined in this way on the maps 29 J Kiruna and 29 I Kebnekaise.

The topographic maps east of the mountains are published on the scale of 1:50 000. Economic maps on the scale of 1:20 000 are also published for the areas below the cultivation line (in Swedish *odlingsgränsen)*. Both types of maps have 5 m contour intervals. Within the areas covered by these maps, certain special maps are available. They are rectified air photos on the scale of 1:20 000 linked to the official coordinate system.

When the regional gravity programme was initiated, the determinations of altitude on the basis of the topographic maps were tested.

In two areas with dense measurements the altitudes of 156 stations were taken from the economic maps and compared to the measured heights. The results show an average error of 1.4 m. RAK has made the same sort of comparison in other areas and has found differences in the order of 2.0–2.9 m (Johansson, Krosse 1964).

Obviously the choice of stations influences the determination of altitude to the same degree as the determinations based on photogrammetry. It is preferable, that the field operator determines the station altitude directly in the field, thus guaranteeing a proper choice of station. To sum up, the various methods available in areas without roads give approximately the same accuracy, but the costs are quite different. The barometer method requires extra equipment and many people, and it can only be used under suitable weather conditions.

Aerophotogrammetric altitude determination is a relatively cheap method and has therefore been used when topographic map material has not been available. Where altitude determinations are possible by means of existing topographic maps, merely no extra costs are incurred during this step in the data production.

## CHOICE OF POINT DENSITY

When the regional measurements for 29 J Kiruna started, the aim was a density of 1 pt/km² and an accuracy of at least 0.2–0.3 mgal. It was mainly economic and practical reasons for the choice of point density. The costs for each point are related to travel time rather than to the number of points measured, which would justify certain revisions in choice. Furthermore, experience gained with respect to identification of local anomalies could be another reason for revising the point density.

As could be expected, it was found that the structural information increased with greater point density. If, for instance, an accuracy of 0.4 mgal is set due to cost estimates, a point distance of less than 300–400 m is of no value. If the measurements are confined to certain profiles, shorter pointdistances can be justified. A pre-requisite for doing the measurements along profiles is previous knowledge about the structure being investigated.

When regional gravity prospecting after nonmagnetic iron ores is performed, the main problem is to identify the local anomaly. Theoretically one can evaluate the largest point distance neccessary for a certain structure to come out clearly, but practically it is a lot more difficult, especially when the regional gravity background is complicated, which for example is the case for the Kiruna map.

Some experiments have been performed to see if one could establish a system for classification of local and regional anomalies. The gravity data for this purpose were selected from places where gravity surveys have been of significant importance. Fig. 3 a shows a bouguer anomaly from the Svappavaara ore district containing the near surface ores Leveäniemi (200 Mt), which give rise to a maximal anomaly of 8.5 mgal, and 2 km further north the Gruvberget ore deposit (70 Mt) with a maximal anomaly of 6.5 mgal. About 2 km east of the ore deposits a regional gravity anomaly of roughly 7 mgal is located above the greenstones of the Svappavaarasyncline. Through statistical treatment of the data we have tried to estimate the probability of discovering a local anomaly of increasing amplitude at different pointdistances. Figs. 3 b and 3 c show anomaly configurations at 400 m and 800 m pointdistances respectively. Now considering the ore anomalies to be local (compared to the regional anomalies further east), and, supposing that at least one point shows a value of more than 4 mgal, the 400 m (net-work) gives a 100 % chance for discovering Leveäniemi but only 60 % for discovering Gruvberget. With an 800 m net the current probabilities are 50 % and 20 %, respectively. One can observe that the regional anomaly does not change very much, whereas the Gruvberget anomaly especially disappears very rapidly, and it is doubtful whether one would react at all when the 800 m net anomaly map is presented.

These considerations and experiences have formed the background for the choice of point density applied to the regional gravity survey (shown in the scale 1:50 000). In other words, separate planning of the measurements is performed with the aid of geological and aeromagnetic information. Measurements over large, homogeneous granites are generally very sparse, i.e. 0.5–1 pt/km$^2$, while the point density within supracrustal areas often amounts to 2–5 pt/km$^2$. In some cases, where "suspicious" anomalies are delineated during the data reduction step, supplementary measurements have been carried out, often using conventionally established profiles. It should be mentioned that lack of data can occur when working in areas, where altitude or position is very difficult to determine.

## INSTRUMENTS, FIELD MEASUREMENTS AND DATA-REDUCTION

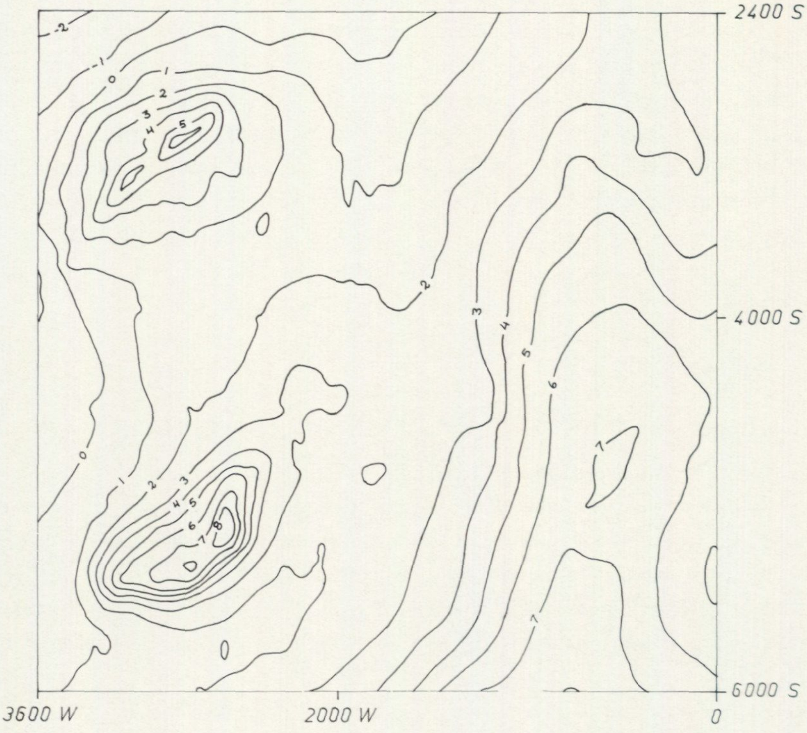
The gravity measurements were carried out using the following types of instruments: Worden Pioneer, Worden Prospector and Worden Master. The instruments are calibrated twice a year along a line from the top of Luossavaara (north of Kiruna) via Kiruna church and a number of RAK points on the road to Vittangi to a RAK-fixed point at Iso Kutujärvi 5 km east of Svappavaara. The calibrating line has a length of 55 km and the gravity difference between the two end points of the line is 102 mgal.

The scale constants of the gravimeters depend on temperature, which is taken into account when the data reduction is performed. Thermometers are carried in the Pioneer and Prospector transport boxes, whereas the Master, which is regulated by a thermostat, has a built-in thermometer. The temperature is recorded a few times a day. During the field-work the two first-mentioned instruments are kept at the prevailing outdoor temperature in order to control the instrumental drift. The measurements are arranged with base-tie stations at a suitable distance from each other, implying that no more than 3 hours of measuring time is spent between measurements at base-tie stations. In this way a considerable part of the tidal effect is included in the correction for the instrument drift. Consequently no separate tidal correction has been carried out to date.

As our measurements are connected with those carried out by RAK, all measurements are in agreement with *"rikets absolutsystem"*. The early regional measurements as well as most of the more detailed surveys were reduced with respect to the older *"absolutsystem"*.

All points in the regional and sub-regional gravity maps are now recalculated to fit the European Calibration System, ESG 62 (Pettersson 1964). Moreover point altitudes are converted from the 1900-year system to the 1970-year system.

No investigation concerning the influence of the air pressure on the gravity instruments has been performed. Such investigations have been made by Lennart Pettersson (Pettersson 1967) on the RAK-Worden Master gravimeter. The results obtained by Pettersson show an air pressure influence on the measure-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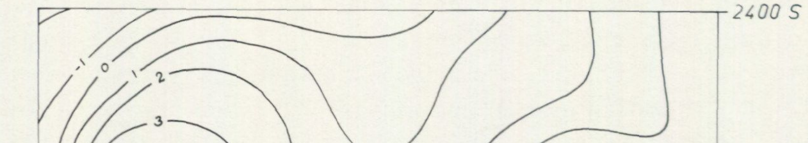
a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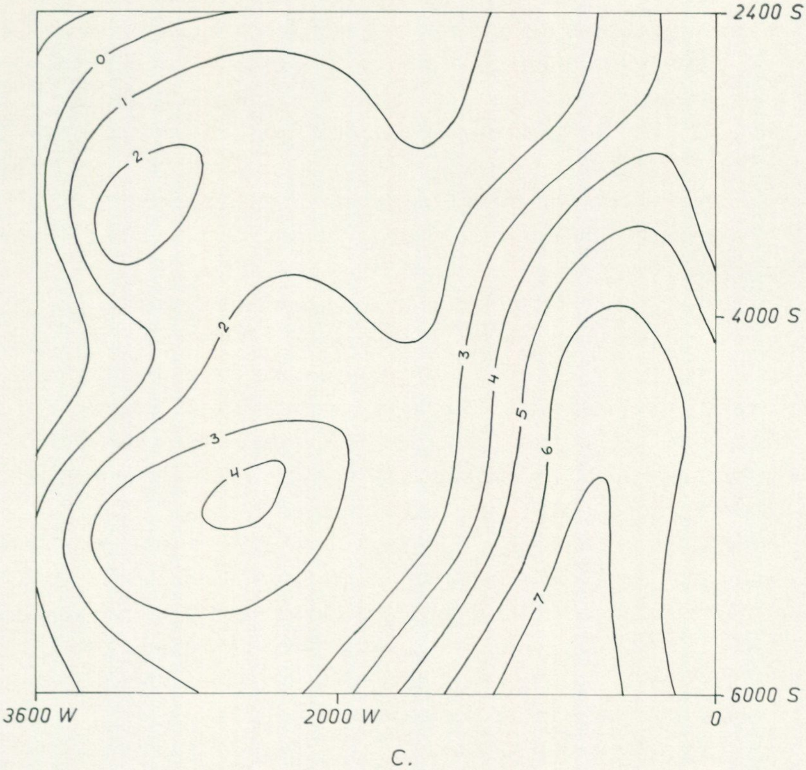

Fig. 3. Bouguer anomaly from the Gruvberget-Leveäniemi area (topographic corrections included):

a) Simplified anomaly picture from detailed measurements.
b) Anomaly picture at a 400×400 m station net.
c) Anomaly picture at a 800×800 m station net.

ments amounting to, at the most, 0.04 mgal pr 100 m change in altitude. The very close correlation of SGU's measurements to the RAK network is a sufficient reason for not doing any data reduction due to pressure changes.

In the ordinary reduction calculations a mean rock density of 2.67 g/cm³ has been used to represent the average rock. The free-air correction used is 0.3086 mgal/m which gives a bouguer correction of −0.1119 mgal/m. The total altitude correction is thus 0.1967 mgal/m.

## LATITUDE CORRECTION

The main gravitational field on the reference spheroid is described by the international formula (1930):

$$\gamma_0 = 978\,049\,(1 + 0.0052884 \sin^2\varphi - 0.0000059 \sin^2 2\varphi)$$

The point identification in the horizontal plane refers to the Swedish coordinate-system 2.5 gon W Stockholms observatorium meridian (xy-coordinates). Calculation of $\gamma_0$ requires evalution of the latitude ($\varphi$), which is possible by using precalculated tables. However, it seemed easier to go the opposite way. From the international formula, tables showing $\varphi$ for discrete valies of $\gamma_0$ – in this case for every milligal – were constructed. A rather voluminous table for the northern part of Sweden turned out to be the result. By means of these tables we are able to construct $\gamma_0$-curves – each 1 milligal apart directly on the field maps. With the aid of a transparent interpolation scale one obtains the main gravity field for stations where measurements have been made.

In this respect it is reasonable to mention the accuracy obtained in locating the stations. By means of the field map material (airphotos, economic or topographic maps) the field operators choose optimal locations for the stations to be measured. Optimal locations mean places that are easily recognizable on the maps, in both the horizontal and the vertical planes.

The position of the stations is marked with a needle on the map. With the greater amount of details offered by the air photos on the scale of 1:20 000, the position of the stations can be determined to within 20 m. The topographic maps, scale 1:50 000 and 1:100 000, give rise to corresponding errors of 50 m and 100 m respectively. These values have to be increased somewhat to account for errors caused by data transference to the final gravity maps.

## TOPOGRAPHIC CORRECTIONS

Before publishing the gravity maps of the Norrbotten and Västerbotten counties an additional topographic correction will be made. The measurements in Jämtland made at the request of "the Geodynamics Projects" have been published without topographic correction. These measurements should, however, have been corrected with respect to topography as should the Nordingrå measurements.

The actual topographic correction is made in two steps, namely a local cor-

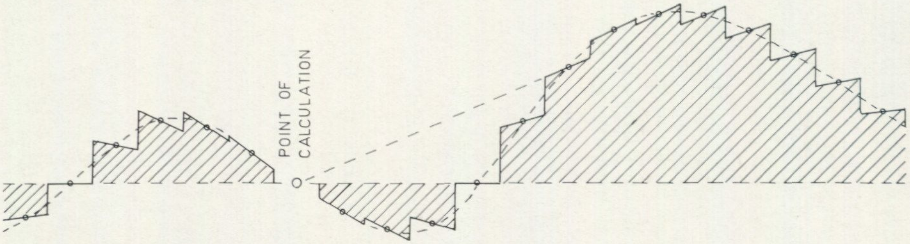

Fig. 4. Representation of the relief by means of inclined terraces. (After L. Granar.)

rection from 0 to 2 km and a distant correction from 2 to 40 km. The calculations are based on the following approximate formula (Granar 1967 and Karlemo 1963):

$$g_t = \frac{G \rho f}{D} \sum_i \sum_j C_{i,j} (h_{i,j} - h_c)^2$$

$G$ = gravity constant

$\rho$ = density

$f$ = adapting factor

$D$ = square unit distance

$C_{i,j}$ = coefficients for local or distant topography

$h_{i,j}$ = height of surrounding points

$h_c$ = height of actual station

Fig. 4 shows the principle of representation of the topography. In this terrace model the topography is expected to be of uniform altitude within a square unit. The topographic correction is based on the best available material (economic maps, special maps or topographic maps). The point altitude are established in a square grid, the distance between the points being 200 m. Computer processing of the data leaves a map with topographic corrections written in the xy-coordinate system. Fig. 5 a shows a topographic correction from an area on 28 M Pajala NV, while Fig. 5 b shows the corresponding topography.

The stations measured by RAK were not corrected with respect to topography, but as quite a number of these measurements have been included in our data material, topographic corrections have now been added.

A representative point collection from the ABEM-gravity measurements within the Kiruna and Malmberget *"Statsgruvefält"* has also been included in our material, implying a topographic correction of this material as well.

## SOME CONSIDERATIONS ABOUT THE ACCURACY OF THE RESULTS

The degree of accuracy obtained is very dependant on the many circumstances under which the measurements are made, and therefore the result should be regarded as a compromise between obtainable accuracy and acceptable expense.

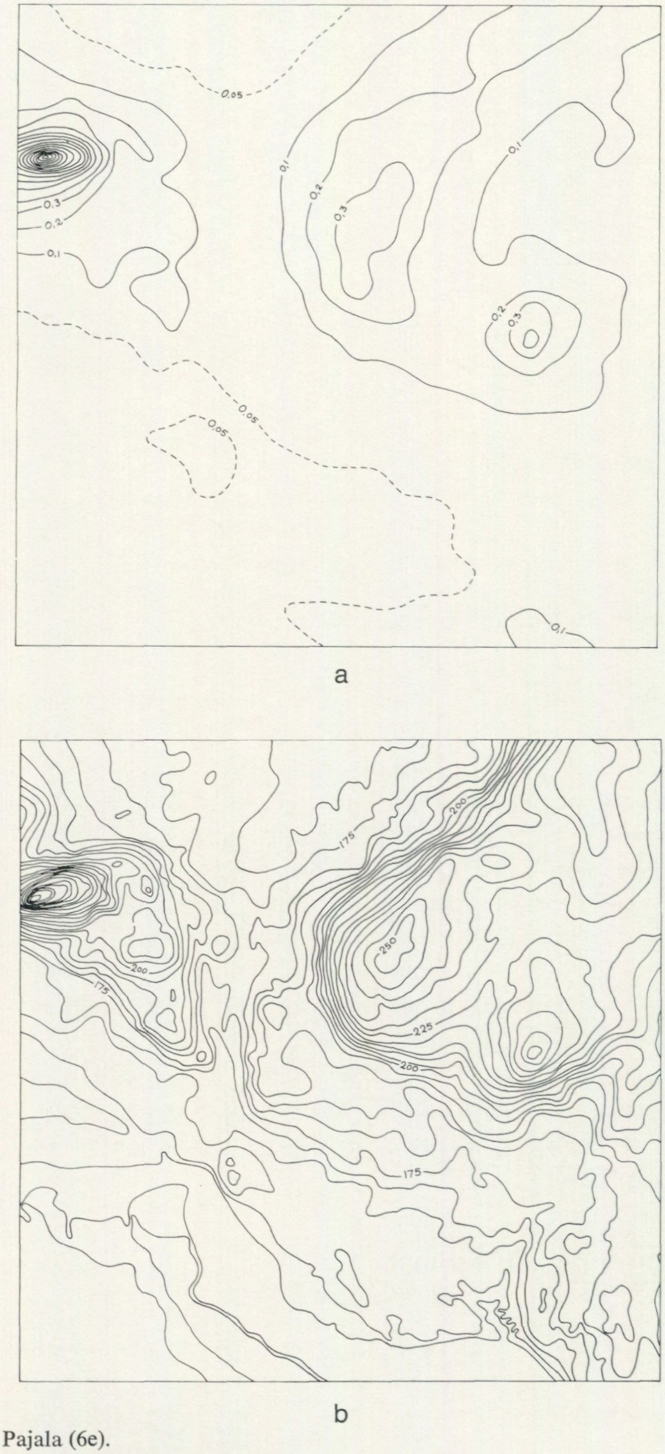

Fig. 5. 28M Pajala (6e).

a) Terraine effect: 0.1 mgal equidistance.
b) Topography: 5 m equidistance.

An analysis of the accuracy thus requires detailed studies of the measuring techniques.

First of all it can be stated that the drift of the gravimeter has no significant influence on the accuracy. A number of control points has been established for each map. These control points are linked to the state system by means of helicopters or snow vehicles in areas without roads. Those stations, which are not control points, are always within 2–3 hours travel time from such a control point, making a determination of the instrument drift to within 0.1 mgal possible in most cases. The precision of the altitude determination is of vital importance for the accuracy of the final result. The methods applied here, i.e. photogrammetry from topographic maps of some kind, are expected to give the altitude to within 2 m. Both methods are, however, very much dependant on the number of reference points of known altitude within an area. In areas with very few reference points, for instance in deserted mountainous areas, the altitude determination is less precise. Here the absolute determination of the altitude may contain greater errors than the ± 2 m mentioned earlier. The conclusion is that the altitude correction cannot be considered to be more exact than ± 0.4 milligal.

In regions of extreme topography, gravity measurements should be subjected to topographic corrections. Normally it is rather easy to evaluate this correction to an accuracy of 0.05 mgal (Granar 1967).

However, a few points in areas of high relief happen to cause trouble due to very rapid changes in the topographic correction.

A summary of the reflections seems to indicate an error of no more than 0.5 mgal. Besides one must realize that such a comprehensive material might contain some erroneous value, being an error either in the reading, the elevation determination or the position. Considerable experience in processing such field data reveals that the above-mentioned type of errors very seldom occurs. It is worth noting here that the field operators taking care of these measurements are highly skilled personnel who knows how to handle the instruments by experience gained through more than 10 years of work in northern Sweden. As most of the operators have been working for SGU since the very beginning of the gravity programme, an unusual degree of continuity links the maps together.

## REGIONAL AND SUB-REGIONAL MAPS

The regional type of Bouguer gravity maps is represented in the scale of 1:50 000 following the topographic map system. Most of the gravity stations are shown on the maps. Under special circumstances, however, when an unusual cluster of points occurs, only a part of these are shown. The anomaly values are given in tenths of milligals and the decimal point defines the position of the station. Fig. 6 shows an example taken from the Bouguer anomaly map 28 M Pajala NV.

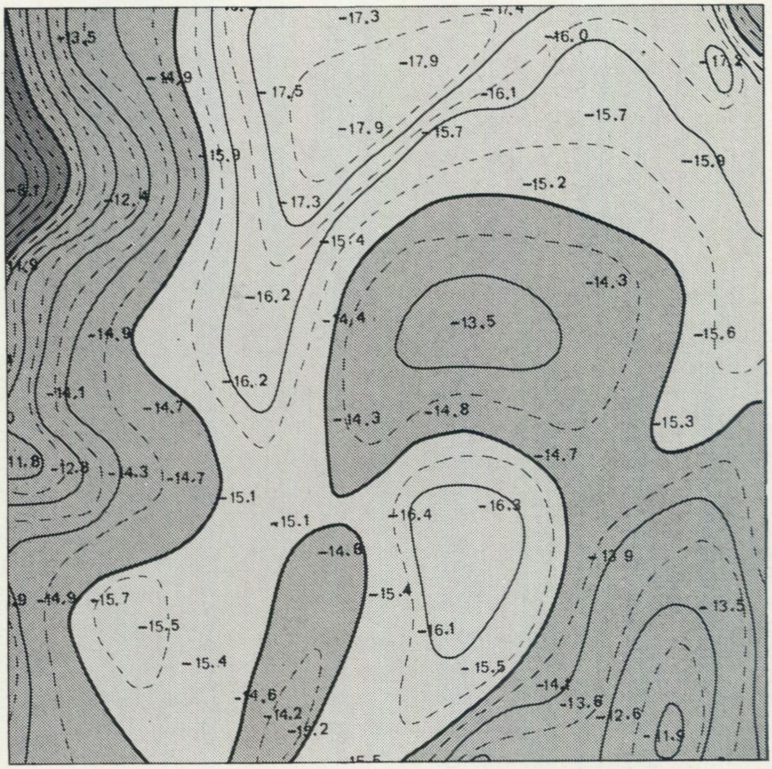

Fig. 6. 28M Pajala (6e).
Bouguer anomaly: 0.5 mgal equidistance.

Isoanomaly curves are drawn as a continuous line for the mgal-niveau, whereas the 0.5 mgal curves are broken lines and the 5 mgal curves are emphasized by heavy lines. A grey tonal range of five different shades is used to accentuate the anomaly picture. The measurements of the sub-regional type are published on the scale of 1:250 000 according to the standard classification of maps used by *Statens Lantmäteriverk* (Fig. 1). These maps do not show the positions nor the anomaly values of the stations due to lack of space. The processing has been made on the basis of the 1:50 000 and 1:100 000 maps.

The measurements along the border zone between Finland and Sweden have been completed with gravity observations from the Finnish region. This was possible due to the kind co-operation of the late Professor Tauno Honkasalo and the Geodetic Institute of Finland. The Finnish gravity values are given in the system IGSN71, and the altitudes also refer to a system different from the one used in Sweden. A transformation to the system ECS62 as well as to the Swedish altitude and coordinate systems has therefore been carried out with the

Fig. 7. 28M Pajala (5 – 6, d – e)
Bouguer anomaly: 1 mgal equidistance.

consent of Professor Honkasalo. The data from Finland covers a 30 km broad belt along the border.

Fig. 7 shows the Bouguer anomaly map 28 M Pajala NV on the scale of 1:250 000. The interval between the isoanomaly curves is 1 mgal and each 5 mgal curve is accentuated with a heavy line. A grey tonal range has been used to increase the resolution of the picture.

Fig. 8. Regional gravity measurements. In areas difficult to approach, the snowscooter is invaluable. Photo S. Blind 1976.

## ACKNOWLEDGEMENTS

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