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On the geophysical investigation in the Virtasalmi area

by Toivo Siikarla

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ON THE GEOPHYSICAL INVESTIGATION IN THE VIRTASALMI AREA

The gravity observations of the Virtasalmi area and the geologic interpretation of the results in conjunction with the results of the magnetic and electromagnetic measurements

BY

TOIVO SIIKARLA

WITH 24 FIGURES AND 26 TABLES IN TEXT, TWO APPENDICES AND FOUR APPENDED MAPS

GEOLOGINEN TUTKIMUSLAITOS
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ABSTRACT

The paper deals with the geophysical investigation in the Virtasalmi area and the geological interpretation of the results obtained.

In the first part of the paper special attention is paid to gravity measurements in order to ascertain whether the methods, developed for gravimetric measurements and reduction on the basis of a survey carried out in small areas, could also be employed for the investigation of extensive areas.

In the last part of the study the physical properties of the rocks in the area investigated are described and a geological interpretation is given to the results of the geophysical measurements performed by various methods.

TIIVISTELMÄ

Tutkimus käsittelee Virtasalmen alueen geofysikaalisia mittauksia ja tulosten geologista tulkintaa.

Tutkimuksen alkuosassa kiinnitetään erityistä huomiota painovoimamittauksiin tarkoituksena selvittää soveltuvatko pienien alueiden mittauksissa kehitetyt painovoiman mittaus- ja redukointimenetelmät myös laajojen alueiden tutkimiseen. Kirjoittaja osoittaa, että mittauspisteiden paikantamisessa ja korkeuden mittauksessa saavutetaan riittävä tarkkuus reduktiolaskujen suorittamiseksi painovoimahavaintoja vastaavalla tarkuudella. Reduktioiden yhteydessä esitetään menetelmä leveysastekorjauksen laskemiseksi Gaussin-Krügerin koordinaatistossa.

Painovoimamittausten loppuvaiheessa suoritettiin erityinen tarkistusmittaus eri aikoina mitattujen osa-alueiden liitosvirheiden määrittämiseksi. Tarkistusmittaus osoitti, että tottuneen henkilökunnan huolellisesti suorittamalla kenttätyöllä voidaan kuvatulla osa-aluemittauksella saavuttaa riittävä tarkkuus 50—100 km² käsittävillä alueilla. Olisi kuitenkin edullisinta yli 50 km² laajuisilla tutkimusalueilla mitata jo työn alkuvaiheessa maastoon pysyvästi merkitty kiintopisteverkko, johon osa-alueet liitettäisiin. Näin voitaisiin työn tarkkuutta valvoa jatkuvasti eri työvaiheiden aikana.

Tarkistusmittauksen yhteydessä suoritettiin sidontamittaus geodeettisen laitoksen painovoimapisteisiin ja määritettiin siirtymäkorjaus geologisen tutkimuslaitoksen painovoima-arvoista geodeettisen laitoksen järjestelmään. Tutkimuksessa esitetään myös siirtymäkorjaus geologisen tutkimuslaitoksen suhteellisista Bouguer-arvoista geodeettisen laitoksen Bouguer-anomalioihin.

Geofysikaalisten mittaustulosten geologista tulkintaa koskevassa osassa kuvataan Virtasalmen alueen geologiset pääpiirteet ja tärkeimpien kivilajien fysikaaliset ominaisuudet, sekä tarkastellaan kivilajien fysikaalisiin ominaisuuksiin perustuvia tulkintamahdollisuuksia. Tutkimuksen lopussa kuvataan eri kivilajien ja geologisen rakenteen ilmeneminen geofysikaalisina anomalioina.

Kirjoittaja osoittaa, että geofysikaalisilla tutkimuksilla on saatu huomattavasti uutta tietoa Virtasalmen alueen geologiasta. Useimpien paljastumista tavattujen kivilajien jatkuminen vesistöjen ja maapeitteen alla ja niiden rajat toisia kivilajeja vastaan on selvitetty geofysikaalisten mittaustulosten avulla. Myös sellaisia kivilajiesiintymiä, joissa ei ole paljastumia, kuten laaja kalkkikivijakso ja eräät ultraemäksiset muodostumat, on paikannettu. Tehostettu paljastumien etsintä ja kaivaukset on voitu keskittää suhteellisen suppeille, mutta tulkinnan kannalta tärkeille avain-alueille.

Virtasalmen tutkimus osoittaa, että geofysikaalisten mittaustulosten geologinen tulkinta edellyttää useamman mittausmenetelmän käyttöä sekä jatkuvaa yhteistyötä geofyysikon ja geologin välillä koko tutkimusvaiheen aikana.

Helsinki 1967. Valtion painatuskeskus

PREFACE

Since 1963 the Exploration Department of the Geological Survey has carried out, under the supervision of Professor Aarno Kahma, Ph. D., extensive regional investigations in Virtasalmi and its surroundings in order to find out what possibilities there are for the existence of economic ore deposits in this area. By now the Hällinmäki copper deposit has been discovered in the area under investigation. The exploitation of the deposit was started by the Outokumpu Co. in the autumn of 1966. The geophysical survey of the Virtasalmi area was carried out under the supervision of the present author, while Mr. Lauri Hyvärinen, Lic. Phil., was in charge of the geological investigations.

The results now published by the author are based, as far as the geophysical investigations are concerned, on the field work done in the years 1963—1965. The field work was under the direct surveyance of research assistants Messrs. Juhani Kankaanpää, Osmo Kinnari and Niilo Puranen. For the determination of the physical properties of the rocks the author received valuable aid from Mr. Matti Ketola, Lic. Tech. The maps and diagrams were drawn by Mrs Sisko Sulkanen. Mrs Gillian Häkli translated the manuscript into English.

The author wishes to express his gratitude to the Director of the Geological Survey, Professor Vladi Marmo, Ph. D., for his most positive attitude towards the present study and for allowing its publication as a Bulletin of the Geological Survey. Further, I want to thank Professor Aarno Kahma, Ph. D., the head of the Exploration Department, for the frank support I have received throughout all stages of the investigation.

Thanks are also due to Dr. R. A. Hirvonen, professor of geodesy at the Technical University, Otaniemi, and Dr. Aimo Mikkola, professor of geology also at the Technical University, Otaniemi, for their valuable advice.

The author is especially indebted to Mr. Lauri Hyvärinen, Lic. Phil., who was in charge of the geological exploration in the Virtasalmi area, and to his colleagues for their pleasant and fruitful cooperation during the study.

The work of the forementioned research assistants and that of their helpers has had a decisive effect on the success of the present investigation. To them all I express my cordial thanks.

Finally, I whish to acknowledge the financial aid received from Suomen Kulttuurirahaston Mikkelin lääninrahasto (The Cultural Foundation of Finland) and from Outokumpu Oy:n Säätiö (The Outokumpu Foundation).

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Toivo Siikarla

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INTRODUCTION

The use of gravity observations for studying the geological structure of the surficial parts of the earth's crust can be considered as having begun about 50 years ago. In 1915 Hugo von Boeck showed that the torsion balance constructed by Roland von Etvös, at the beginning of the century, could be used for the location of synclines and anticlines, whose inner parts were composed of heavier or lighter rocks than the surroundings. Since experience had shown that salt and oil deposits were associated with these types of geological formations, exploration was started rapidly due to the great economic interest involved.

According to Dobrin (1960) the first geological torsion balance measurements were made in the years 1915—1917, on some already well-known salt deposits in Czechoslovakia and Germany. The search for oil employing torsion balance measurements got under way in the United States of America in 1922. This led to the discovery two years later of the so-called Nash dome oil deposit in Texas. Pendulum apparatuses were also used in the search for oil besides torsion balance measurements. According to Nettleton (1940) the Gulf Oil Corporation measured many thousands of pendulum stations in the years 1930—1935.

As early as 1918 the Swedish geophysicist G. Ising had suggested the use of the gravimeter for measuring gravity differences, but the development of the gravimeter cannot be said to have begun until the beginning of the 1930's. In 1932 Hartley (1932) presented his new gravimeter, and at the end of the decade several other new types of gravimeter were introduced. The development of the gravimeter continued with great intensity, concentrating, not only on improving the accuracy of measurements, but also on the reduction of the weight and size of the instruments in order to ease their handling in the field.

New types of gravimeter were developed also in Scandinavia, for example, those of Nörgaard and Boliden. The Boliden gravimeter was constructed especially for ore-exploration measurements (Lindblad and Malmquist 1938). In 1947 the Houston Technical Laboratory constructed the Worden gravimeter, with which, in the following year, G. P. Woollard carried out a world-wide tying of gravity base-stations (Woollard 1950).

The first attempt in Finland at applying gravity measurements to ore-exploration was made in 1946, when the present Professor Tauno Honkasalo, at the request of the Geological Survey, measured several profiles at Lampinsaari, Vihanti, using a Nörgaard gravimeter. In Autumn 1947 the Geological Survey bought a Boliden gravimeter from Sweden, with which measurements were carried out between the years 1948—1953. In 1954 and 1955 Finland procured for ore-exploration three Worden gravimeters which were delivered to the Vuoksenniska Co., the Outokumpu Co. and the Geological Survey. By the end of 1965 the number of gravimeters for ore-exploration and geological research had increased to ten, of which eight were Worden gravimeters and two were World-Wide gravimeters constructed on a similar principle. At the same time the number of exploration organisations using the gravimeter had increased from three to six.

The adoption of Worden gravimeter decisively influenced the development of gravimetry for ore-exploration. The relatively large size and weight of the former gravimeters as also their insufficent accuracy had led to the fact that the measurements had to be limited to gravity profiles, whose location was determined in accordance with indications given by other geophysical methods. In order to eliminate the irregular and uncontrollable instrumental drift the so-called trippel-method was used, by which three observations were carried out alternately at each station. Thus the final number of stations was only a third or fourth of the total number of observations. Under these circumstances it was economic impossibility to cover the area under exploration with an even and sufficiently dense network of observation stations. The usage of gravity survey was limited chiefly to the classification of other geophysical anomalies, mainly with the intention of explaining whether the conducting zones established by electric measurements were caused by compact sulphides or so-called sulphide-bearing schists.

It was not until the execution of gravity observations began to approach other geophysical methods both in measuring speed and in cost that a start could be made using them together with other methods also in areal research. Now it is no longer merely a problem of finding anomalies indicating ore but also of reaching conclusions concerning the geological structure of the area under exploration in as much detail as possible, taking advantage of the results of other geophysical methods and geological observations. A picture of the growing popularity of gravity measurements is given by Fig. 1, in which the number of gravity measurements carried out in connection with ore-exploration is shown for periods of one year from 1948—1965.

The facts are based on material collected by the Research Committee, appointed by the Society of Mining Engineers, of which the present author is chairman. Although there is a temporary drop in the number of observations for the two years following 1958, the general trend has been strongly in the ascent, as can be seen from Table 1.

The stations are distributed over many research objects situated in different parts of the country. Most of them are relatively small, merely a few square kilometres in area. The Virtasalmi region which is discussed in the subsequent text is probably the largest coherent area of exploration covered by a dense network of stations.

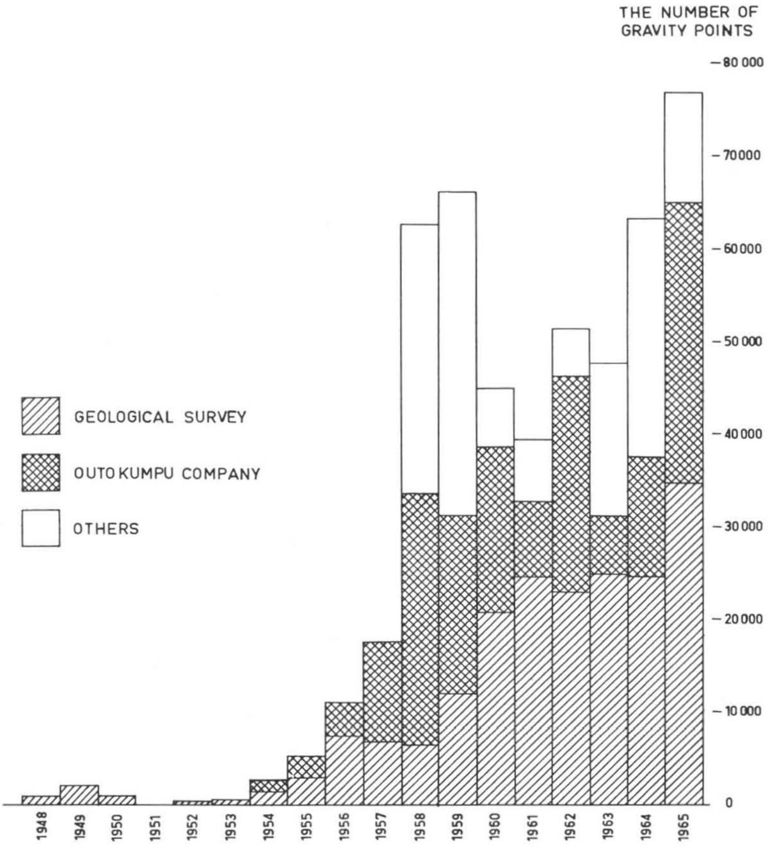

FIG. 1. The number of gravity stations measured in Finland in connection with ore exploration in the years 1948—1965.

TABLE 1

The number of gravity stations measured in connection with ore exploration in Finland over five-year periods.

Year	Number of measured stations
1948—1950	3 290
1951—1955	8 186
1956—1960	202 310
1961—1965	279 203
Total	492 989

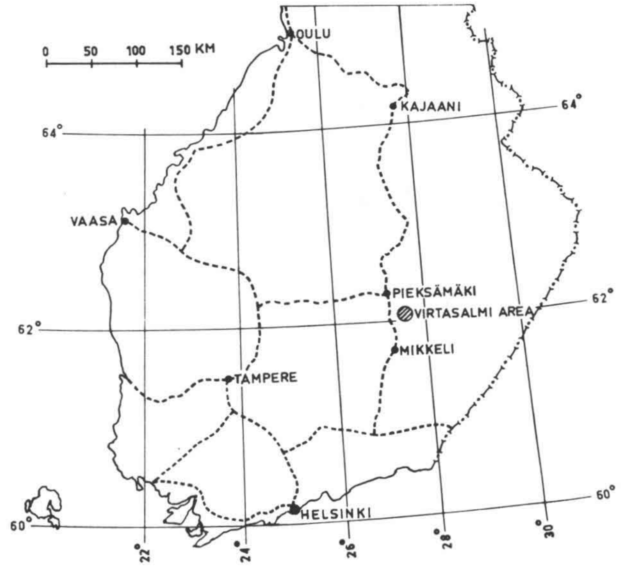

FIG. 2. The location of the Virtasalmi area.

SITUATION AND TOPOGRAPHY OF THE VIRTASALMI AREA

The exploration area of Virtasalmi (Fig. 2) is situated in the province of Mikkeli, about 60 kilometres north-northeast of the town of Mikkeli and includes the southern part of the commune of Virtasalmi plus parts of the communes of Juva and Joroinen. The terrain of the area is covered mainly by gently undulating forestland. The greatest differences in elevation are 45—55 metres, the main altitude of the area being about 130 metres above sea-level. The highest hills are generally covered by moraine, with farmhouses and fields at their tops.

There are many lakes and ponds linked by rivers and streams. The largest lake, Lake Virmasjärvi, whose length is about 11 kilometres and breadth at the widest 2 kilometres, divides the research area into two parts, the main part of which is situated to the west of the lake. There are three largish lakes in the north-western part of the region, Ankeleenjärvi, Haapajärvi and Herajärvi. The waterways of the area have made the carrying out of consistent geophysical measurements difficult. However, magnetic and electromagnetic measurements have been carried out with consistency during the winter when the waterways are frozen. It has not been possible to extend gravity observations to the lakes.

The network of roads is fairly dense. Besides the highways there are passable forest and farm roads, which have eased the transportation of exploration equipment and work groups.

REVIEW OF THE GEOPHYSICAL STUDY OF THE REGION

In 1953 the Geological Survey carried out aeromagnetic measurements in the vicinity of Pieksämäki covering an area of 3 600 km² as part of a national survey. Flights were performed at a height of 150 metres above the surface of the earth and along parallel lines, with distances of 400 metres between them. Measurement of the earth's total magnetic field was done with a Canadian fluxgate magnetometer which was installed in a bi-motor Lockheed Lodestar aeroplane. The air-borne magnetic measurements were supplemented in 1956 by air-borne electromagnetic measurements, the purpose of which was to confirm the electrically conducting zones in the bedrock. The electromagnetic measurements comprised an area of roughly 1 200 km² in the south of the Pieksämäki region.

The aeromagnetic survey showed a strong anomaly zone lying in the same direction as the Juva — Pieksämäki road (Fig. 3). The main part of the zone runs from the cross-roads at Narila, in the northern part of Juva commune, northwestwards to the western side of the village of Virtsalmi. From here it continues to Vehmaskylä, on the border of the Virtasalmi and the Pieksämäki communes, where it branches out into several parts. Air-borne electromagnetic measurements confirmed that the zone contains also conducting parts.

In the years 1950, 1953 and 1961 some limited areas of the above-mentioned anomaly zone were studied by geophysical measurements carried out on the ground. The objects were chosen on the basis of the aerogeophysical survey and the ore-boulders found in the region.

In 1963 detailed electromagnetic and magnetic exploration was carried out over an area of 4 km² in the southern part of the zone in the vicinity of the Narila cross-roads. At the beginning of 1964 it was extended to include the whole zone from Narila to the village of Virtasalmi. In addition to the electromagnetic and magnetic measurements, also gravity observations were connected to the exploration programme. At the same time, detailed geological mapping and a search for ore-boulders was started together with the geophysical measurements.

By the end of 1964 an area of about 91 km² had been measured both electromagnetically and magnetically, entailing about 64 300 observation stations or an average 707 observation stations per square kilometre. Gravity observations had been carried out simultaneously over an area of 40 km² with 22 900 observation stations, their density being about 570 to the square kilometre. During the year 1965 geophysical surveying was continued in addition to the measurements made on other areas.

By the end of 1965, 167 km² of the Juva—Virtasalmi region had been explored electromagnetically and magnetically, comprising about 112 500 observation stations or an average of 673 stations to the square kilometre. Likewise, gravity measurements had been carried out over an area of 89 km² with altogether 51 140 stations, their average density being 587 stations to the square kilometre.

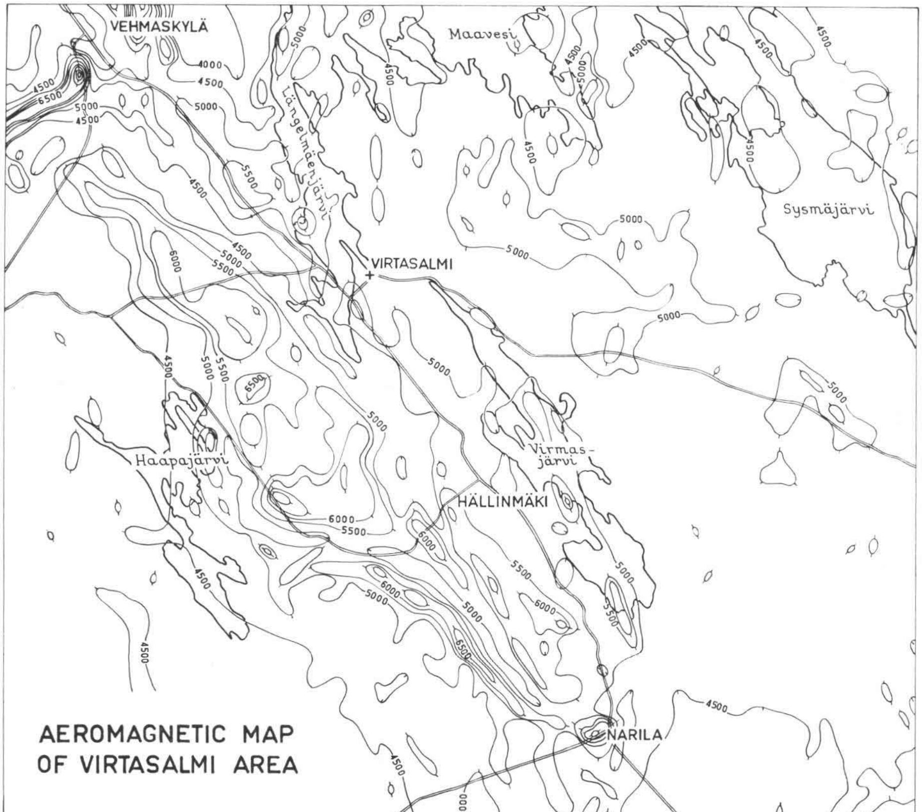

FIG. 3. A simplified aeromagnetic map of the Virtasalmi area.
The contour interval of the total intensity is 500γ.

Systematic magnetic observations were made using a Finnish ARM-magnetometer, by measuring the vertical component of the earth's magnetic field. Electromagnetic measurements were carried out over the whole area by the Slingram method, the frequency of the primary field being 3 600 Hz. Electromagnetic measurements were also made over a part of the region by the Turam method at a frequency of 820 Hz, employing a long cable earthed at both ends in order to genarate the primary field. In connection with the exploration of the so-called Karsikumpu copper deposit at Hällinmäki, a certain amount of magnetic three-component logs were made in drill holes. Gravity observations of the region were made employing the American Worden gravimeter. Fig. 4 shows the boundaries of the geophysically explored region.

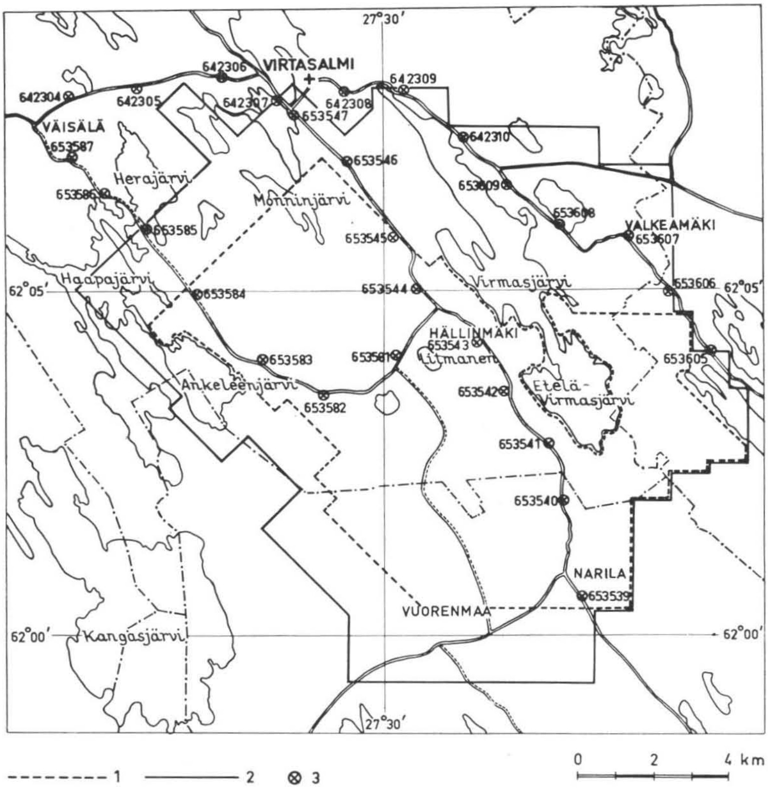

FIG. 4. The areas investigated geophysically in the years 1964—1965. 1, Area measured gravimeterically; 2. Area surveyed magnetically and electromagnetically; 3. The bench marks of the National Board of Survey.

STAKE-LINES

The setting-out of the stake-lines

The customary net of stake-lines was used to locate the geophysical observation stations. Thus, staked squares of 2 km x 2 km were set up over the terrain. These were divided up into strips of equal width by parallel lines, so-called auxiliary lines, spaced 500 metres from each other.

The lines cut through the terrain were staked out at 50 metre intervals, each stake being marked with its respective coordinates.

The sides of the squares, the so-called base-lines, were ranged by a Wild theodolite, and staked out taking into consideration corrections needed for the slope of the terrain. The starting directions of the auxiliary lines were set at right-angles to the base-lines using a prism square and the lines were staked out visually.

Since there were no triangulation stations near-by when the staking of the stake-lines was started, they could not be tied to the Gauss-Krüger coordinate system. Therefore, the bearing of the line net had to be determined by astronomical observation. The preliminary coordinates were worked out with the accuracy afforded by an aerophotographic map with a scale of 1 : 20 000.

On the basis of the aeromagnetic anomalies, it was clear that the x-y coordinate system would only be suitable as a basis of exploration in the Virmasjärvi region and to the east of the lake. To the west of the Juva—Virtasalmi road the general strike of the rocks was roughly N45°W according to the aeromagnetic anomalies, which would entail that measurement lines running east—west or south—north would cut the strike of the rocks most disadvantageously. Therefore, to the west of the road the coordinate axes were rotated 45°, thus forming a new separate coordinate system denoted by K and L. In this way, the K-axis had a bearing of N 45° E with the increasing values of coordinates to the north-east. Similarly the L-coordinates increased to the north-west. The coordinate system has the common point.

$$x = 6\,878.000.0 \qquad K = 150.000.0$$
$$y = 531.000.0 \qquad L = 50.000.0$$

The total length of the stake-lines made by the Geological Survey in the Virtasalmi area was about 500 km. In Fig. 5 the stake-lines are presented schematically.

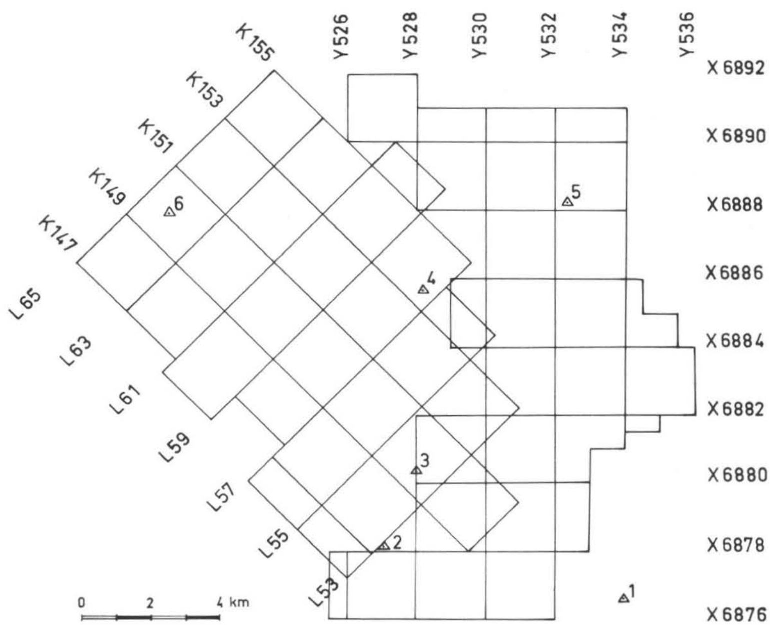

Fig. 5. The scheme of the stake line system in the Virtasalmi area. Triangulation stations: 1. Rutkonmäki; 2. Vuorenmaa; 3. Rajakangas; 4. Hällinmäki; 5. Rahkolanmäki; 6. Louhumäki.

The tying of the stake-lines to the Gauss-Krüger coordinate system

In 1964 the National Board of Survey rebuilt some triangulation towers in the region under discussion and in the following summer measured new triangulation stations of the lower order. The Geological Survey received the coordinates of the new stations in the summer of 1966. Thus the stake-lines could be tied to the national net and their relative accuracy worked out. The tying was achieved by theodolite traversing from five triangulation stations placed within the staked area and from one triangulation station outside it. The triangulation stations used in the tying are marked in Fig. 5. The aim of the tying measurements was to determine both the difference in coordinates and the direction of the lines.

In Table 2 the results of the tying measurements of the x-y lines are compiled. The $\triangle x$- and $\triangle y$ values in the table were obtained by subtracting the line coordinates of the tying stations from the Gauss-Krüger coordinates of the same stations.

TABLE 2

The deviations of the x-y -lines from the Gauss-Krüger Coordinate System

Tying-station	$\triangle x$ m	$\triangle y$ m	Direction of x-axis
1. Rutkonmäki	— 14.5	— 0.3	0^c00
2. Vuorenmaa	— 18.7	+ 11.6	399^c91
3. Rajakangas	— 19.7	+ 8.1	0^c01
4. Hällinmäki	— 19.5	+ 11.0	0^c04
5. Rahkolanmäki	— 17.1	+ 10.2	0^c03

The systematic difference in coordinates is due to the initial values of the line coordinates selected with the aid of an aerophotographic map. According to the checking measurement the coordinate systems are practically parallel to each other. If the transfer of the line coordinate system is conducted so that it receives a correction

$$\triangle x = -18.0 \text{ m}$$
$$\triangle y = +10.0 \text{ m}$$

then the following differences (Table 3) emerge between the line coordinates and the Gauss-Krüger coordinates for different parts of the exploration area.

TABLE 3

Relative deviations of the stake-line system in different parts of the exploration area.

Tying Station	$\triangle x$ m	$\triangle y$ m
1. Rutkonmäki	+ 3.5	— 10.3
2. Vuorenmaa	— 0.7	+ 1.6
3. Rajakangas	— 1.7	— 1.9
4. Hällinmäki	— 1.5	+ 1.0
5. Rahkolanmäki	+ 0.9	+ 0.2

Diagonal lines marked *L* and *K* are tied to triangulation stations 2, 3, 4 and 6, of which the latter is right in the north-west part of the *L*-*K*-line system. Based on the *K*-*L* -line station near triangulation-station 3 (Rajakangas), the coordinates of which in the Gauss-Krüger and the *K*-*L* coordinate system are as follows:

$$K = 149.500.0 \qquad x = 6\ 880.274.4$$
$$L = 53.749.2 \qquad y = 528.008.0$$

the Gauss-Krüger coordinates of the tying stations were calculated assuming the direction of the *K*-axis to be 50^c000 and using for the computation of the coordinates, the differences $\triangle K$ and $\triangle L$ of the actual diagonal system. Thus the differences between the actual *K*-*L*-coordinates and the ideal coordinates (Table 4) were obtained.

TABLE 4

Differences between the *K*-*L* -coordinates and the ideal coordinates expressed in *x* and *y*.

Tying Station	$\triangle x$ m	$\triangle y$ m	Direction of K-axis
2. Vuorenmaa	+8.3	+3.4	50^c04
3. Rajakangas	0	0	—
4. Hällinmäki	—0.9	+2.4	50^c10
6. Louhumäki	+0.2	+5.7	50^c01

Checking measurements showed that the differences between the stake-line coordinates and the ideal coordinates are so small that they are unimportant when, for example, correcting gravity observations.

GRAVITY MEASUREMENTS IN THE VIRTASALMI AREA

Elevation measurements of the gravity stations

Levellings

In gravity measurements connected with ore-exploration the elevation of observation stations should be determined so that the same accuracy is obtained in the free-air and Bouguer reduction as in the gravity observations themselves. When working with a Worden gravimeter, the observation accuracy of which is of the order of 0.01 mGal, the elevation of the observation stations must be known to an accuracy of at least 5 cm. This can usually only be obtained by levelling. When making gravity observations over an extensive coherent area it is difficult even in levelling to prevent errors from accumulating and the elevation from drifting slightly if there is no reliable network of bench marks. This is due to the fact that levelling must proceed gradually in accordance with the progress of the actual gravity measurements. Since calculations connected with the observations are made simultaneously with the gravity measurements, completed elevation values must be available. Levelling cannot be done all at once over the whole area beforehand, because a certain amount of stake-line stakes always disappear from fields and road-edges. Thus the levelling net of a large area consists of different sub-areas with no common reduction.

At the start of the gravity measurements there were no bench marks available in the Virtasalmi area, so the starting elevation of the levelling was chosen arbitrarily. The levellings were carried out with a self-balancing Zeiss Ni 2 levelling instrument in closed loops along stake-lines. In this way the elevations for each stake were obtained.

In the summer of 1965, the National Board of Survey performed levellings in the area between Juva and Pieksämäki. One of the traverses followed the Juva—Virtasalmi—Pieksämäki highway cutting across the whole exploration area. A second traverse went from Hällinmäki past Lake Ankeleenjärvi, and a third extended in part over the exploration area, to the east of Lake Virmasjärvi.

In order to check the Geological Survey's levellings and to obtain the difference in plane between the N_{43} system[1]) and the Geological Survey's arbitrary elevation system, tying levellings were made to nine bench marks of the National Board of Survey, situated in different parts of the Virtasalmi exploration area.

The results of the tying measurements are compiled in Table 5.

TABLE 5

The results of the tying levellings between N_{43} system and the arbitary elevation system of the Geological Survey (G. S.)

Bench mark No	Elevation N_{43}	Elevation of the G. S.	Difference N_{43} — G. S.	Difference from mean m
653 539	144.13	112.54	31.59	+0.04
653 540	136.50	104.94	31.56	+0.01
653 541	119.33	87.79	31.54	—0.01
653 542	125.28	93.71	31.57	+0.02
653 543	156.27	124.71	31.56	+0.01
653 581	108.27	76.80	31.47	—0.08
653 582	118.48	86.92	31.56	+0.01
653 605	149.18	117.66	31.52	—0.03
653 606	147.25	115.69	31.56	+0.01
		Mean	31.55	
		Mean error ± 1.2 cm		

The difference between the Geological Survey's elevation system and the N_{43} elevations is 31.55 m. Comparison measurements gave a mean error of 1.2 cm to this difference in plane, thus demonstrating that the accuracy of the levelling done by the Geological Survey is fully sufficient for the calculations of gravity observations.

[1]) An elevation system used by the National Board of Survey.

Formerly it used to be the custom to level the elevations of all observation stations. In this case the measuring lines running between the stake-lines usually had to be cleared at least in part and the observation stations marked with stakes in order to ease the levelling. Since 1960 the Geological Survey has used a method, whereby only the elevations of stakes on the stake-lines are levelled and the elevations of observation stations between the stake-lines are measured employing a specially constructed liquid-mercury elevation difference meter simultaneously with the gravity observations. This method has achieved a reduction in essential expenditure with no reduction in accuracy of measurement.

Elevation measurements using a liquid-mercury elevation difference meter

The liquid-mercury elevation difference meter, the so called levelling tube, was developed originally by chief geologist Heikki Paarma, M. A., and Mr. O. Kangassalo (Paarma and Kangassalo 1962, 1964, 1965) of the Otanmäki Co. The present author (Siikarla 1966) has earlier described in detail the construction and operation of the instrument as well as the measurements carried out with it. The device consists of a large liquid container A, a narrow tube B provided with a scale and a mercury container C (Fig. 6). The liquid container is connected by a plastic tube to the scale tube B, which is fixed to the mercury container C. In containers A and B the surface of the liquid is in connection with the open-air. For transport the instrument is provided with the essential valves which prevent sudden movements of the liquids.

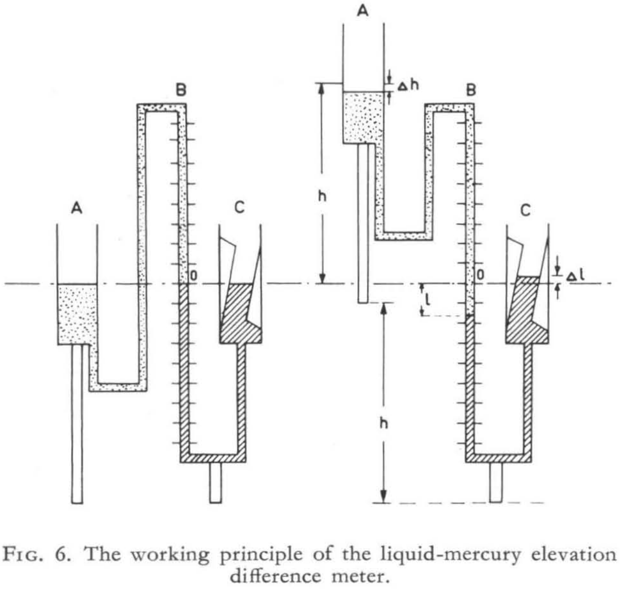

FIG. 6. The working principle of the liquid-mercury elevation difference meter.

The container A and the scale tube with the mercury container are provided with supporting legs. When both of them are resting on the same horizontal plane the top surface of the liquid in container A, the boundary surface of the liquid and mercury in scaled tube B and the top surface of the mercury in container C all settle at the same horizontal line, which is chosen as the scale's zero point. The scale can be moved in a vertical direction in such a way that the zero point of the scale coincides with the boundary surface of the liquid and mercury.

When measuring the elevation difference (h) the boundary surface of the liquid moves the distance (l) on the scale. As the author has shown earlier (Siikarla 1966) the following equation holds between h and l:

$$l = \frac{1}{\left(1 + \frac{B}{C}\right)\frac{\delta_1}{\delta} + \frac{B}{A} - 1} \cdot h \qquad (1)$$

where A = cross section area of liquid container
B = cross section area of scaled tube
C = cross section area of mercury container
δ_1 = density of mercury
δ = density of liquid

Equation *(1)* can be rewritten in the form

$$h = \alpha \cdot l \qquad (2)$$

where the scale factor $\alpha = \left(1 + \frac{B}{C}\right)\frac{\delta_1}{\delta} + \frac{B}{A} - 1$

The scale can be made to show directly the elevation differences to be measured. The diameters of the containers and the densities of the liquids impose certain limits on the value of the scale factor. By constructing the container C in such a way that its cross section area can be regulated, α can be adjusted to exactly its right value, should, for example, the density of the liquids change.

The levelling tube constructed and used by the Geological Survey is depicted in Figs. 7 and 8. On the left (Fig. 7) is the cylinder-shaped liquid container, which is made of transparent acryl plastic, with the supporting leg and on the right is the

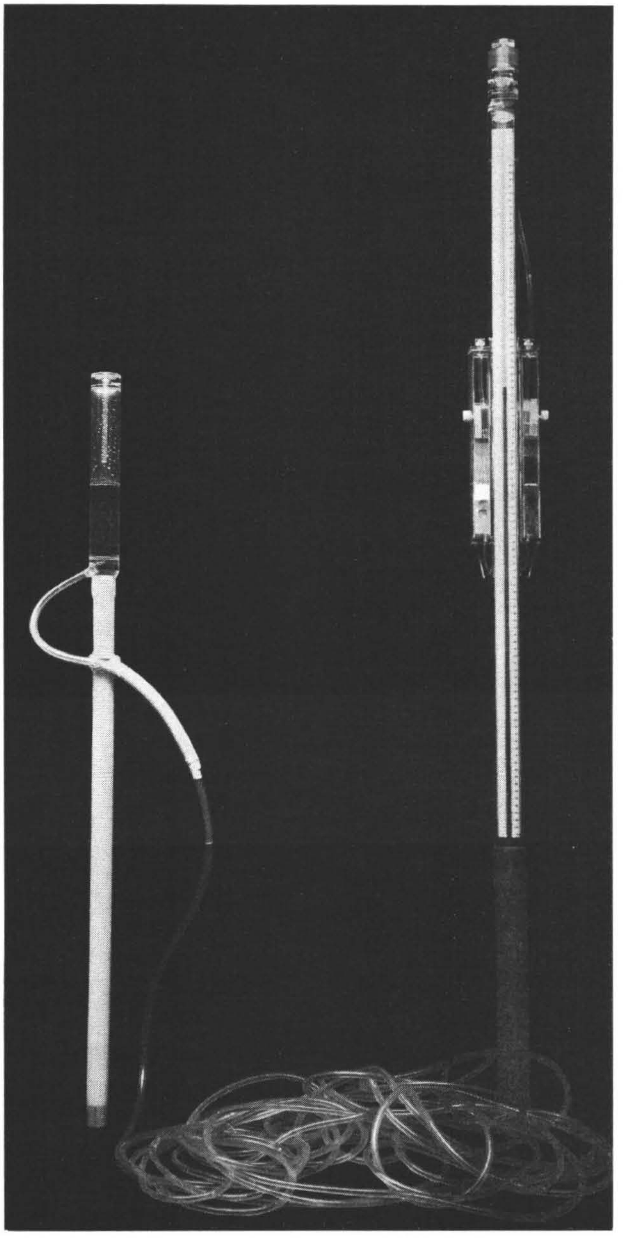

FIG. 7. The liquid-mercury levelling tube used in the investigation at Virtasalmi. On the left is the liquid container and on the right the scale tube with the mercury containers. In the centre is the connecting hose, 20 metres in length.

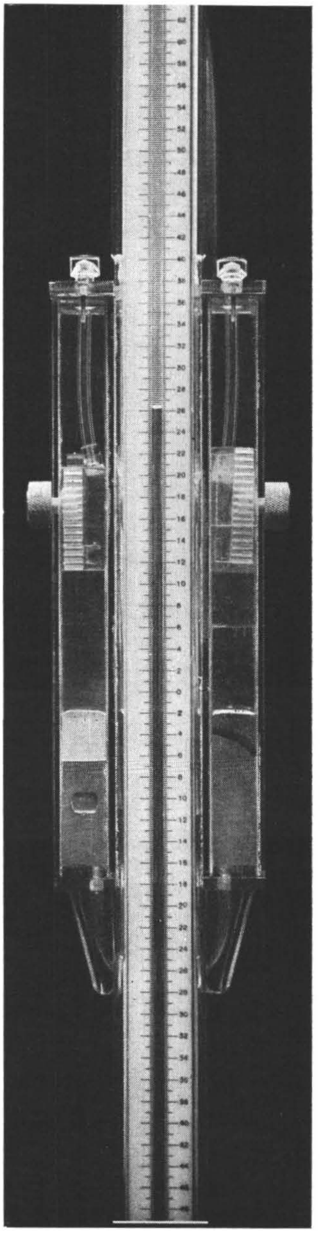

FIG. 8. The scale of the levelling tube and the mercury containers on both sides of it. The mercury containers have been provided with knobs for regulating the area of the mercury.

scaled tube with its mercury container. In the centre a 20 metre long flexible plastic tube joins the liquid container to the upper end of the scaled tube. In Fig. 8 the construction of the scaled tube and the mercury containers can be seen in more detail. The engraved scale and the liquid-mercury tube in front of it are inserted in an acryl tube about 40 mm in diameter, so that the illumination of the scale is as good as possible under all conditions. There are two mercury containers symmetrically on both sides of the outer tube protecting the scale. The knobs with which the area of the mercury in the containers can be changed are visible on the sides of the containers.

The elevations of the gravity stations between the stake-lines were determined by measuring the elevation differences of consecutive stations with a levelling tube. The differences in elevation were observed straight on the tripod of gravimeter. When the distance between the parallel stake-lines is 500 metres and the first and last stations of the connecting line are situated at a stake-line stake, then normally 25 elevation differences are measured by levelling tube on each line. The levelling tube measurement begins and ends at a stake-line stake, the elevation of which has been levelled. In this way the errors of the levelling tube observations do not accumulate. The error of closure which has formed between the stakes is shared evenly between all the stations. In formal field work the mean error is $\pm$ 2 cm per measured elevation difference (Siikarla 1966).

The Geological Survey has measured almost 150 000 gravity stations with a levelling tube. Elevation differences of $\pm$ 5 metres can be measured with the device now in use. Should the elevation difference of the consecutive stations exceed 5 metres, then it can be measured in several steps with the aid of intermediary stations. Instead of the normal elevation scale, the present levelling tube is provided with a scale giving immediately the value of the combined free-air and Bouguer reduction corresponding to the elevation difference between the stations.

Procedure of gravity measurements

General

Field measurements are carried out by a crew consisting of a research assistant, 2 observers and 3 helpers. The research assistant is an employee of the Geological Survey who receives a monthly salary. The observers are paid by the hour but are in regular employment, only the helpers are engaged from the district in question.

The research assistant directs the local measuring work and calculates results during the survey. The latter entails computation of the relative Bouguer values for the observation stations taking into consideration the free-air and Bouguer reduction arising from the elevation of the stations, and also the latitude correction caused by the position of the observation station. Thus the possible errors in observations can be corrected and those areas determined in which the station net should be made denser or the direction of the measuring lines changed.

At the start, the observation station system forms a rectangular grid of 20 $\times$ 100 metres so that the distance between the measuring lines going from one stake-line to the other is 100 metres and the distance between the stations along the measuring line is 20 metres. Efforts are made to carry out the survey in such a way that the measuring lines cut the strike or contacts of the rocks as much at right angles as possible. The spacing of the stations parallel to the strike may be wider than perpendicular to it, because the physical properties of the rocks change more slowly in the direction of the strike. After preliminary handling of the observation data, the station grid is made denser to 20 $\times$ 50 metres where necessary.

The survey of the area under exploration is performed in two phases. The first phase is the so-called base measurement, which consists of the gravity observations made on the stake-line stakes. At this point the crew divides into two, with one of the observers attending to the gravity observations on the stake-lines and the other seeing to the levelling of the stakes. The second phase, which consists of gravity observations on the measuring lines between the stake-lines, is carried out by the whole crew as a body because the elevation differences of the observation stations are measured with a levelling tube simultaneously.

If two gravimeters are available the base measurements and levellings can be done at the same time as those of the measuring lines, in which case one extra observer and one helper must be added to the crew. This method speeds up the work considerably.

The final extent of the area to be measured cannot usually be determined at the beginning of the survey. For this and some other reasons the exploration of even a large area consists of sub-areas surveyed at different times and later joined together The continual joining of sub-areas can easily lead to an accumulation of errors such as plane differences between sub-areas. In order to confirm these errors a separate checking station net was measured at the end of the research in the Virtasalmi area using as accurate an observation method as possible. This base net was compared with the gravity values of the stake-line stakes near to it.

The gravity observations in the Virtasalmi region were made with a gravimeter of the Worden Pioneer Standard type, whose constant is 0.0930. The instrument has not been recalibrated by the Geological Survey but the constant given by the manufacturer has been employed.

Gravity measurements on the stake-lines

In the observation area the stake-lines form a fixed station net, in which the measuring stations are permanently marked in the terrain with 80 cm high wooden stakes. The essential fixed station net for the sub-area under survey is established by gravity observations made at the stake-line stakes. The ends of the measuring lines between the stake-lines are tied to the fixed station net, and using this net the sub-areas are joined up.

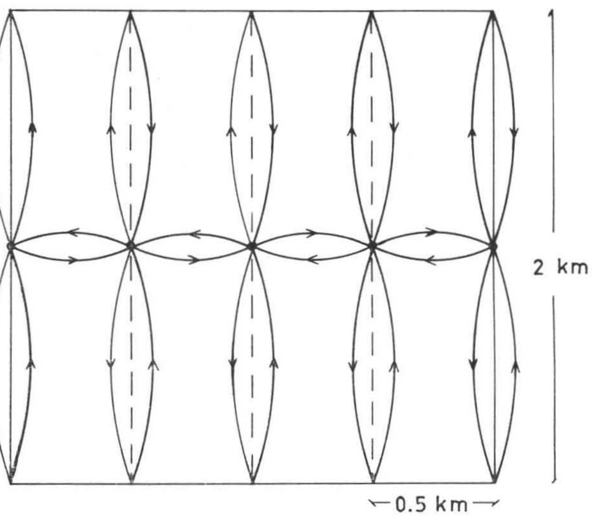

FIG. 9. Scheme showing how the gravity observations are carried out along the stake lines.

An area between 3—6 km^2 in size and bounded by parallel stake-lines is selected as a sub-area. The length of the sub-area is determined by the distance between the two base-lines (2 km), its breadth varying from 1 to 3 km (Fig. 9).

The measuring of a stake-line begins in the middle of the line, from where observations are carried out in both directions in loops going back and forth and closing up at the starting point. The measurement of one loop lasts about an hour when the distance between stakes on the line is 50 metres. The error of closure obtained is presumed to have been caused by the drift of the gravimeter. It is eliminated by dividing the error equally between each observation station. It is advisable to carry out the measurements under as favourable weather conditions as possible.

The stake-lines are tied together with measurements made several times in a transverse direction. Efforts are made to carry out the tying measurements through the central part of the area by making use of e.g. a road cutting through the area. In this way the measuring time between the observation stations situated on different lines becomes as short as possible.

The elevation of the stake-line stakes is levelled and the relative Bouguer values are calculated for the stakes taking into consideration the free-air, Bouguer and latitude corrections.

Gravity measurements between stake-lines

The greatest part of the stations in the area is situated on the measuring lines between the stake-lines. Each measuring line begins at a stake-line stake and ends at the corresponding stake of the following stake-line. The line is determined by means of a compass and the gravity observations are made every 20 metres. The measuring crew has three gravimeter tripods, a levelling tube, a light 20 m steel tape and a gravimeter. The jobs of the crew's 5 members are as follows:

— 1st observer carries out the measurements with a gravimeter

— 2nd observer reads the levelling tube and acts as recorder, writing in the note-book the time for observations, the reading of the gravimeter and the elevation difference between stations.

— 2 helpers, one at each end of the levelling tube, transport it and see to the orientation.

— 1 helper acts as tripod mover.

Starting out from stake P_0 the measuring progresses in the following way:

P_0 P_1 P_2 P_3 P_4 P_5 P_6

1) Tripods at stations P_0 and P_1, and the elevation measurement by tube between $P_0 — P_1$. Recorder at station P_0.

2) Levelling tube moves forward and a helper sets tripod at station P_2.

3) Gravity observation at station P_0. Levelling tube between stations $P_1 — P_2$. Recorder at station P_1 writes down the gravity value and reads the elevation difference between $P_1 — P_2$ from the levelling tube.

4) Observer moves from station P_0 to P_1 taking with him the tripod which the helper brings to station P_3. The levelling tube is moved between $P_2 — P_3$.

This arrangement permits smooth progress. Since the gravimeter is always 20 metres away from the rest of the crew at the moment of observation, the movements of the members of the crew do not disturb the gravity observations.

The method is also fairly quick. In the summer of 1965 the crew described above measured 14 700 stations in 69 days, that is an average of 213 stations a day.

The Bouguer values for the measuring line stations are calculated from the fixed value of the stake-line, taking into consideration the observed gravity values, the combined free-air and Bouguer reduction values given by the levelling tube measurements and the latitude correction. Thus the error of closure obtained from the fixed gravity value of the second terminal point includes

1) the drift of the gravimeter and
2) the elevation error induced by the levelling tube measurements.

These sources of error are eliminated by dividing the error of closure between all intermediate stations.

In principle the latitude correction can be disregarded at the stations on the measuring line. Its effect can be included in the forementioned closing error. It is not considered until the closing error is reduced, because the latitude correction is the same between all stations due to the fact that the stations are at an equal distance from each other.

Reduction of gravity measurements

The gravity observations in the Virtasalmi area were reduced to the zero level of the Geological Survey's elevation system, which is 31.55 metres above the zero level of the elevation system N_{43}.

The altitude of the top of the gravimeter tripod was taken as the elevation for the observation station. The elevation difference between the top of the tripod and the surface of the ground was not corrected separately with the coefficient of the free-air reduction, but the measured gravity values were corrected directly from the height of the tripod to the reduction plane, with the aid of the combined free-air and Bouguer reduction coefficient.

The latitude correction is based on the rectangular co-ordinates of the observation stations and was carried out in the manner to be described later in more detail.

Due to the smoothly sloping terrain no topographic correction was made.

Free-air reduction

The point of free-air reduction is to transfer the gravity observations to the reduction plane disregarding the mass between the observation station and the reduction plane. The reduction coefficient showing the magnitude of the vertical gradient ($d\gamma/dh$) of the gravity is, according to Garland (1965),

φ	$\frac{d\gamma}{dh}$
60°	— 0.30844 mGal/m
65°	— 0.30841 »
70°	— 0.30838 »

Thus, the value of the gradient is dependent on the latitude, but the change is so small, that the constant value 0.3084 mGal/m can be used for the whole area of Finland.

Separate free-air reduction was employed at Virtasalmi only in special measurements while, for instance, reducing the observation from the height of the tripod to the elevation of the bench mark situated on the surface of the rock. The actual observation stations were corrected by using the combined free-air and Bouguer reduction coefficient.

Combined free-air and Bouguer reduction

The coefficient 0.2000 mGal/m was chosen when employing combined reduction. If the free-air reduction coefficient has a value of 0.3084 mGal/m the value of the Bouguer coefficient included in the combined coefficient is —0.1084 mGal/m, corresponding to the average density of 2.59 g/cm^3 of the Bouguer plate. The density selected differs from the value 2.67 g/cm^3 generally used, the corresponding Bouguer coefficient of which would be —0.1119 mGal/m. A rounded value (0.2000) was selected as coefficient to simplify calculations made in the field, because from 30 000 to 40 000 gravity stations are measured annually.

The selection may also be justified geologically. In an area of bedrock the use of a density value which would correspond to the actual conditions is very difficult, since, in a strongly folded area for example, the rocks form almost vertical slab-like bodies, in which, in horizontal direction, the densities may vary over a short distance between 2.5 and 3.2 g/cm^3. In addition, under conditions such as in Finland, the Bouguer plate in many cases contains overburden, the density of which varies between 1.2 and 2.0 g/cm^3. If, for example, the reduced elevation is presumed to be 100 m, and the corresponding Bouguer plate composed of soil, whose thickness is 10 metres and density 1.8 g/cm^3, and of rock with a density of 2.67 g/cm^3, then their Bouguer correction is 10.84 mGal. The average density 2.59 g/cm^3 selected for the whole plate gives 10.82 mGal, respectively.

Since the variation in thickness of the overburden in the Virtasalmi area is unknown, all the stations of the area were corrected using the same combined free-air and Bouguer reduction coefficient (0.2000). Thus the effect of the variation in the thickness of the overburden is incorporated in the anomaly pattern obtained.

Latitude correction

The magnitude of the gravity is dependent on the geographical latitude of the observation station. Normal gravity can be calculated from the international gravity formula established in 1930, which, according to Heiskanen and Vening Meinesz (1958), is

$$\gamma = 978\,049\,(1 + 0.0052884\ \sin^2\varphi - 0.0000059\ \sin^2 2\,\varphi) \qquad (3)$$

The change in normal gravity ($\triangle\gamma$) corresponding to the latitude difference $\varphi_1 - \varphi_0$ is obtained from the previous equation. It is

$$\triangle\gamma = 5\,172.3\,(\sin^2\varphi_1 - \sin^2\varphi_0) - 5.7\,(\sin^2 2\varphi_1 - \sin^2 2\varphi_0) \tag{4}$$

Formula (*4*) gives the normal gravity change in milligals when it is moved from latitude φ_0 to latitude φ_1. The magnitude of the latter term e.g. at latitude $\varphi = 62°$ is 0.03 mGal when $\varphi_1 - \varphi_0 = 10'$. The mutual position of the observation stations in gravity measurements connected to ore-exploration is always determined with the aid of rectangular coordinates. The change of normal gravity in a north-south direction can be computed according to the formula given by Nettleton (1940).

$$K = 0.8122 \sin 2\varphi \tag{5}$$

where K denotes the change of gravity in milligals per kilometre. Along the coordinate axis, which differs from the northern direction of angle α, the change of gravity is

$$K = 0.8122 \sin 2\varphi \cdot \cos\alpha \tag{6}$$

In calculating the relative Bouguer values in the Virtasalmi area the influence of latitude was taken into consideration in such a way that a certain correction value was given to the area's station ($x = 6\,878.0$ $y = 531.0$). The other observation stations received a latitude correction with a magnitude

$$K \cdot \triangle x$$

where $\triangle x$ means the coordinate difference between the observation station and the base station. The value of K was the same over the whole area, that is $K = 0.670$ mGal per kilometre in a north-south direction. The correction for each station was calculated with an accuracy of 0.01 mGal, which is sufficient if the accuracy in localisation of the line system and the observation stations is taken into consideration.

The fact that latitude correction has been treated only as a function of the x-coordinate gives rise to some errors which will be examined in the following chapter.

Latitude correction in the Gauss-Krüger coordinate system

If the positions of the observation stations were determined using geographical coordinates and the influence of the latitude were calculated from the formula

$$\triangle\gamma = 5\,172.3\,(\sin^2\varphi_1 - \sin^2\varphi_0) - 5.7\,(\sin^2 2\varphi_1 - \sin^2 2\varphi_0)$$

where φ_1 is the geographic latitude of the observation station and φ_0 the geographic latitude of the selected base station, the obtained correction would be as correct as possible. In trying to achieve an accuracy of 0.01 mGal, φ would have to be determined with an accuracy of at least 0.01 minutes of arc.

When carrying out gravity observations connected with ore-exploration, in which the observation stations are tied to a rectangular stake-line net, the location of the stations is known with sufficient accuracy but the calculation of the latitude correction on the basis of rectangular coordinates causes difficulties for the following reasons:

1) The change in normal gravity is not a linear function of the x-coordinate of the Gauss-Krüger coordinate system.
2) The y-axis does not run parallel to latitude, that is, the latitude correction does not remain constant along the y-axis.

Nettleton (1940) and Parasnis (1962, 1966) have paid attention to the forementioned facta. They presume that in calculating the latitude correction according to the formula

$$K = 0.8122 \sin 2\varphi$$

K can be taken as being linear for a distance of about 1 minute of arc, after which a new value for K and a new base latitude is selected. The method gives sufficient accuracy but is troublesome to use in practice.

The difficulties mentioned in point 2 emerge in an extensive exploration area which is several kilometres wide also in an east-west direction. This problem has not, to the author's knowledge, been treated in detail in literature. The reason for this is probably that gravity observations in more extensive areas have usually been based on a relatively sparse net, in general about 1 km by 1 km, in which case the location of the observation stations is determined in geographical coordinates with the accuracy obtainable from the maps available. Since, however, the survey of also more extensive areas using a very dense station net tied to stake-lines has attained actuality there is reason to examine the problem more closely.

According to Rehn (1933) the Gauss-Krüger x-coordinate is related to the geographical latitude as follows

$$x = B + \frac{N \sin\varphi \cdot \cos\varphi}{2\varrho^2} \cdot \lambda''^2 + (x) \qquad (7)$$

where B = the length of the arc of mid-meridian between the equator and latitude φ
N = radius of transversal curvature
(x) = residual term whose effect can be neglected here
λ = difference in degree of longitude, in seconds, from the mid-meridian
ϱ = 206 264″8

Formula *(7)* can be rewritten

$$x = B + (\mathbf{1}) \cdot (\mathbf{2}) \cdot \lambda''^2 \qquad (8)$$

$$\text{where } (\mathbf{1}) = \frac{\sin \varphi}{2\varrho} \text{ and } (\mathbf{2}) = \frac{N \cos \varphi}{\varrho}$$

The values of (**1**) and (**2**) are listed in Table 6 in steps of 0°.30′.

Formula (*8*) shows that the distance between the y-axis (x = constant) and a given latitude is directly proportional to the second power of the difference in degree of longitude measured from the mid-meridian. The magnitude of the transition is obtained if we write

$$\begin{aligned} x_2 &= B + (\mathbf{1}) \cdot (\mathbf{2}) \cdot \lambda''^2_2 \\ x_1 &= B + (\mathbf{1}) \cdot (\mathbf{2}) \cdot \lambda''^2_1 \\ \hline x_2 - x_1 &= (\mathbf{1}) \cdot (\mathbf{2}) \cdot (\lambda''^2_2 - \lambda''^2_1) \end{aligned}$$

The formula
$$\triangle x = (\mathbf{1}) \cdot (\mathbf{2}) \cdot (\lambda''^2_2 - \lambda''^2_1) \qquad (9)$$

gives the transition in metres when λ_1 and λ_2 have been expressed in seconds and (**1**) and (**2**) taken from Table 6.

TABLE 6

The values of the coefficients (**1**) and (**2**)

φ	(1) · 10^5	diff.	(2)	diff.
61°00′	0.2120	10	15.0306	2 368
61°30′	0.2130	10	14.7938	2 380
62°00′	0.2140	10	14.5558	2 391
62°30′	0.2150	10	14.3167	2 402
63°00′	0.2160	9	14.0765	2 413
63°30′	0.2169	10	13.8352	2 424
64°00′	0.2179	9	13.5928	2 434
64°30′	0.2188	9	13.3494	2 444
65°00′	0.2197	9	13.1050	2 455
65°30′	0.2206	8	12.8595	2 464
66°00′	0.2214	8	12.6131	2 475
66°30′	0.2223	8	12.3656	2 483
67°00′	0.2231	9	12.1173	2 494
67°30′	0.2340	8	11.8679	2 502
68°00′	0.2248	7	11.6177	2 512
68°30′	0.2255	8	11.3665	2 520
69°00′	0.2263	8	11.1145	2 529
69°30′	0.2271	8	10.8616	2 537
70°00′	0.2278		10.6079	

Example 1. $\varphi = 62°$ $\quad (\mathbf{1}) = 0.2140 \cdot 10^{-5}$ $\quad (\mathbf{2}) = 14.5558$

$$\lambda_1 = 0$$

$$\lambda_2 = 10' = 600'' \qquad 600^2 = 36 \cdot 10^4$$

$$\triangle x = \frac{0.2140}{10^5} \cdot 14.558 \cdot 36 \cdot 10^4 = 11.21 \text{ m}$$

Example 2. $\lambda = 62°$

$$\lambda_1 = 1°20' = 4\,800''$$

$$\lambda_2 = 1°30 = 5\,400''$$

$$\lambda_2{}^2 - \lambda_1{}^2 = 29.16 \cdot 10^6 - 23.04 \cdot 10^6 = 6.12 \cdot 10^6$$

$$\triangle x = \frac{0.2140}{10^5} \cdot 14.558 \cdot 6.12 \cdot 10^6 = 190.7 \text{ m}$$

Near the meridian the transition is only 11.2 metres with a movement of 10 minutes away from it. Since 10 minutes equals 8.726 km the transition is 12.8 m/10 km. Because the change of the normal gravity in x-direction ($d\gamma/dx$) is 0.673 mGal/km, the corresponding change in y-direction equals 0.009 mGal/10 km. The necessary accuracy (0.01 mGal) is achieved in an area about 11 kilometres wide on both sides of the mid-meridian even by omitting $d\gamma/dy$.

On the border of the area (example 2) $\triangle x = 190.7$ m/10', and the change of 10 minutes in latitude corresponds to a change of 8.731 km in y-coordinate. Thus $\triangle x = 21.8$ m/km and $d\gamma/dy = 0.015$ mGal/km.

The above example demonstrates that the change in normal gravity in y-direction can be omitted near the mid-meridian, but that further away from the meridian the exploration region has to be divided into suitable sub-areas running in a south-north direction for the calculation of the latitude correction.

In practice, a basic map sheet with a scale of 1 : 20 000 and covering an area of 10×10 km can be taken as a survey unit. The change of gravity in x-direction $d\gamma/dx$ is computed from Nettleton's formula by employing the mean value of φ for the map sheet; $dx/d\lambda$ is calculated with the aid of formula (*9*), and the value of $d\lambda$ expressed in metres is measured from the map for the computation of $d\gamma/dy$. At the lower end of the map sheet a point is chosen, which can be, for instance, the lower west corner. An arbitrary correction — say $1000 \cdot 10^{-2}$ mGal — is given to that point. For the y-axis running along the south margin of the map sheet the $d\gamma/dy$ - corrected values are calculated in such a way that the map sheet becomes subdivided into strips running in a N-S-direction. Along the south border of each strip the corrected value can be taken as constant. The base correction values of the strips change in steps of 0.01 mGal from one strip to another, the width of a strip depending on the distance from the mid-meridian. Efforts should be made to place the borders of the strips so that they coincide with the stake-lines.

On the accuracy of the latitude correction in the Virtasalmi area

As has been mentioned before the latitude correction in the Virtasalmi area was made disregarding the gravity change along the y-axis. Since in the area under consideration the greatest length in y-direction is 15 km — between y-coordinates 521 and 536 — and $d\gamma/dy = 0.005$ mGal/km, the normal gravity decreases 0.075 mGal over a distance corresponding to the whole length of the area in the positive direction of the y-axis.

Because the point $x = 6\,878.0$, $y = 531.0$ was originally selected as base station the latitude correction in the most western part would be $10 \cdot 0.005$ i.e. 0.05 mGal too big and the correction of the easternmost part $5 \cdot 0.005$, i.e. 0,025 mGal too small.

In fact the error is not distributed that evenly, due to the rounding errors and the inaccuracy arising from the transferring of the corrections to the K-L coordinate system.

In Fig. 10 errors induced by the latitude correction in different parts of the exploration region are marked. The errors have been computed by subtracting the correction used in the original calculations from the actual latitude correction. The unit is 0.01 mGal. Although the error at its largest is 0.08 mGal it does not have any noteworthy effect on the anomaly pattern since areally it changes so slowly.

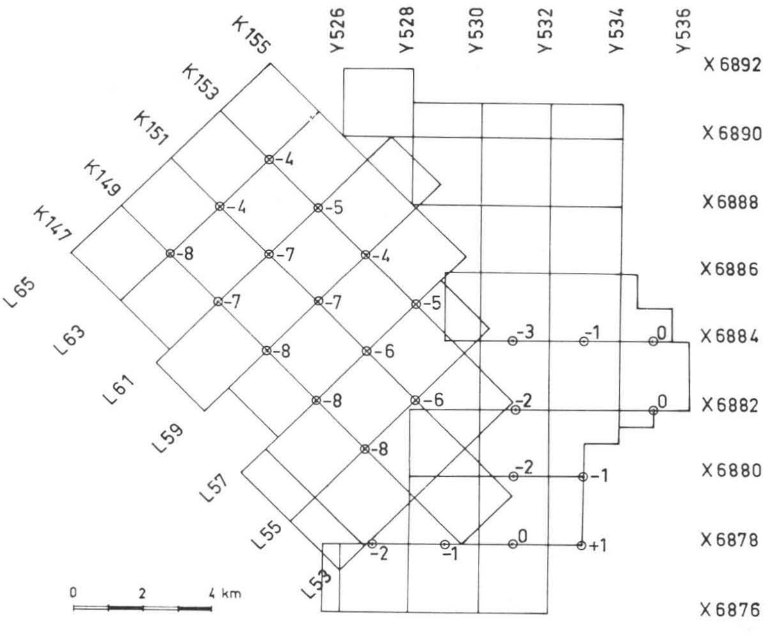

FIG. 10. The areal distribution of errors due to the method used for the computation of the latitude correction. The unit is 0.01 mGal.

Control measurements

The setting-up of a control station net

In November 1965 a special control station net was measured in the Virtasalmi area in order to detect the errors which had arisen at the joining up of the sub-areas measured at different times. The gravity values calculated with the aid of this net were compared with the data of the stake-line observations.

Those bench marks erected by the National Board of Survey in the summer of 1965 which were situated conveniently along the roads cutting the region were chosen as control stations.

Only by the side of the so-called Luomanen road three new stations were built corresponding to the stake-line stakes. Their coordinates are as follows:

Station A	$K = 148.50$	$L = 51.60$
Station B	$K = 149.50$	$L = 54.00$
Station C	$K = 151.00$	$L = 55.60$

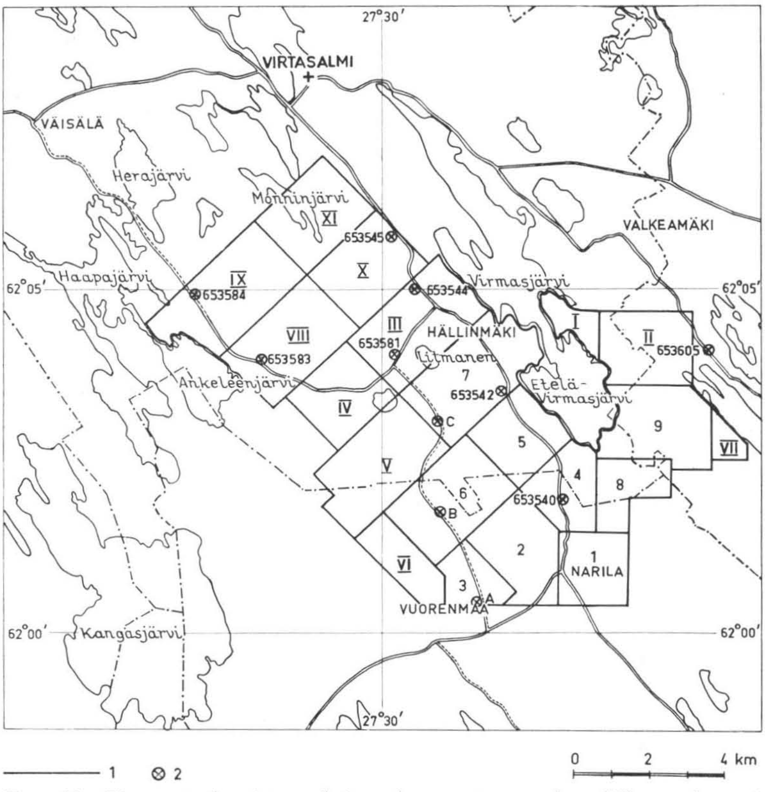

FIG. 11. The control points and the sub-areas measured at different times. 1. The borders of the sub-areas; 2. The control points used for tying. The numbers inside the sub-areas indicate in wich order the observations were carried out. 1—9 were measured in 1964, I—IX in 1965.

The situations of the control stations as well as the sub-areas are shown in Fig. 11.

The control stations formed two closed loops and one separate station sequence (Fig. 12). Loop I consisted of 14 stations and loop II of 10 stations. The separate sequence III had 8 stations. Sequence III could not be formed as a closed loop because there are no road connections on the southern side of Lake Virmasjärvi.

A total of 11 comparison stations in various parts of the exploration area was obtained by tying 8 control stations to the stake-line stakes near-by, and by including stations A, B and C. The tying measurements were performed from the same control stations to 2—4 different stakes, so that changes which had occured in the heights of the stakes, for example, would not effect the results very much. The control stations used for the tying are marked separately on the map (Fig. 11).

With the aid of the tying measurements carried out in the vicinity of control station 653 540, a gravity value was calculated for this station which corresponds to the gravity value of the stake-line net.

Starting from the gravity value obtained for station 653 540, gravity values were computed for all other control stations from the gravity differences measured between them.

Since the gravimeter was above the bolts at the stations of the National Board of Survey and lower than the top of the stakes at the stake-line stations the gravity values were free-air reduced to the elevation of the stations in question.

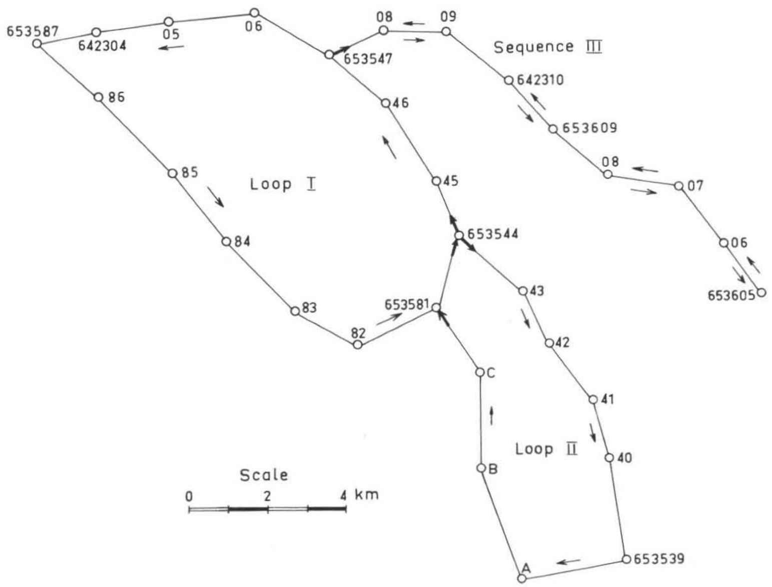

FIG. 12. The scheme showing control loops I and II and sequence III in the Virtasalmi area.

Starting from the gravity values of the control stations, the gravity values of the stakes were calculated on the basis of the tying measurements and compared to the values obtained from the original stake-line survey. By assuming the results of the control station net to be correct, the errors of the stake-line stations were computed.

The determination of gravity values for the control stations

Control station loops I and II

Loops I and II were measured by the so-called trippel-method. This entails observing the station at three different times. The principle of the method is given by the scheme in Fig. 13, where the measuring order of the stations A, B, C, D and E is presented.

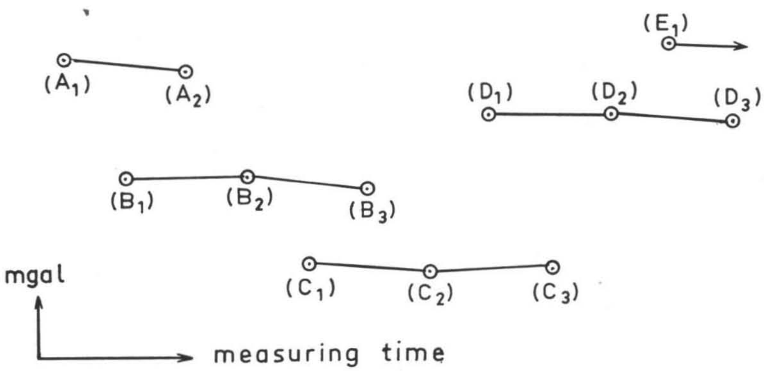

FIG. 13. The principle of the trippel method. The scheme indicates in which order the points are measured.

The measured gravity differences of the stations can be obtained either graphically or arithmetically. If the observations made at the same stations are marked in order of time with the sub-indices 1, 2 and 3, e.g., for station B: gB_1, gB_2 and gB_3 and if it is presumed that the drift in the time between two observations recorded at the same station is linear, the observation of the A station can be interpolated to moment (B_1) and the observation at the station B to moment (A_2). The former can be denoted $gA(B_1)$, which means: observed gravity at station A at the moment (B_1), and the latter $gB(A_2)$, respectively. The gravity difference between stations A and B is then

$$gA - gB - \frac{gA_{(B_1)} - gB_1 + gA_2 - gB_{(A_2)}}{2} \tag{10}$$

that is, the average value of gravity differences obtained. The arithmetical method was employed when processing the Virtasalmi data.

Tables 7 and 8 depict the observations on loops I and II and their reductions to the elevation of the observation stations.

The following symbols are employed in the tables:

$\triangle h$ height of gravimeter tripod in centimetres
T observation time
L gravimeter reading
g'' observed gravity value, 10^{-2} mGal,
r_h free-air correction deduced from height of tripod
g' gravity value, 10^{-2} mGal, reduced to elevation of station

The gravity values of the control stations (g') from Tables 7 and 8 have been arranged into the special computing tables in the order of observations times, so that they form the left-hand diagonal column (Appendices I and II).

At each station the measured values have been corrected to the observation time of the neighbouring station in the following way.

The measured stations are A and B, the observation times T_1, T_2, and T_3 and the corresponding observation values gA_1, gB_1 and gA_2, respectively. Arranged into a table these are:

	A	B
T_1	gA_1	
T_2	(gA)	gB_1
T_3	gA_2	

The gravimeter drift between $T_3 - T_1$ is $gA_2 - gA_1$, and between $T_2 - T_1$ it is:

$$\frac{(T_2 - T_1) \cdot (gA_2 - gA_1)}{T_3 - T_1}$$

The value (gA) of station A corresponding to moment T_2

$$(gA) = gA_1 + \frac{(T_2 - T_1) \cdot (gA_2 - gA_1)}{T_3 - T_1} \tag{11}$$

TABLE 7

Loop I: The observations and their reduction.

Observation station	$\triangle h$	T	L	g''	r_h	g'
65 35 44	+48	12h20	77 65	7 221.5	+14.8	7 236.3
45	+36	26	82 87	7 706.9	+11.1	7 718,0
44	+48	30	77 65	7 221.5	+14.8	7 236.3
45	+36	33	82 88	7 707.8	+11.1	7 718.9
46	+38	38	88 59	8 238.9	+11.7	8 250.6
45	+36	44	82 89	7 708.8	+11.1	7 719.9
46	+38	49	88 60	8 239.8	+11.7	8 251.5
47	+50	53	89 32	8 306.8	+15.4	8 322.2
46	+38	58	88 60	8 239.8	+11.7	8 251.5
47	+50	13h02	89 32	8 306.8	+15.4	8 322.2
64 23 06	+50	08	85 48	7 949.6	+15.4	7 965.0
65 35 47	+50	13	89 34	8 308.6	+15.4	8 324.0
64 23 06	+50	20	85 49	7 950.6	+15.4	7 966.0
05	+43	26	84 95	7 900.4	+13.3	7 913.7
06	+50	31	85 51	7 952.4	+15.4	7 967.8
05	+43	36	84 95	7 900.4	+13.3	7 913.7
64 32 04	+48	43	80 78	7 512.5	+14.8	7 527.3
64 23 05	+43	48	84 96	7 901.3	+13.3	7 914.6
64 32 04	+48	53	80 80	7 514.4	+14.8	7 529.2
65 35 87	+44	59	78 32	7 283.8	+13.6	7 297.4
64 32 04	+48	14h08	80 82	7 516.2	+14.8	7 531.0
65 35 87	+44	15	78 34	7 285.6	+13.6	7 299.2
86	+42	20	78 73	7 321.9	+13.0	7 334.9
87	+44	25	78 34	7 285.6	+13.6	7 299.2
86	+42	30	78 74	7 322.8	+13.0	7 335.8
85	+44	35	81 06	7 538.6	+13.6	7 552.2
86	+42	41	78 75	7 323.8	+13.0	7 335.8
85	+44	46	81 06	7 538.6	+13.6	7 552.2
84	+42	51	81 78	7 605.5	+13.0	7 618.5
85	+44	57	81 06	7 538.6	+13.6	7 552.2
84	+42	15h03	81 79	7 606.5	+13.0	7 619.5
83	+45	09	76 65	7 128.5	+13.9	7 142.4
84	+42	15	81 80	7 607.4	+13.0	7 620.4
83	+45	21	76 67	7 130.3	+13.9	7 144.2
82	+50	27	79 59	7 401.9	+15.4	7 417.3
83	+45	33	76 67	7 130.3	+13.9	7 144.2
82	+50	38	79 60	7 402.8	+15.4	7 418.2
81	+44	44	84 17	7 827.8	+13.6	7 841.4
82	+50	49	79 61	7 403.7	+15.4	7 419.1
81	+44	56	84 18	7 828.7	+13.6	7 842.3
44	+48	16h01	77 78	7 233.5	+14.8	7 248.3
81	+44	08	84 19	7 829.7	+13.6	7 843.3
44	+48	14	77 80	7 235.4	+14.8	7 250.2

The gravity differences ($\triangle g'$) of the stations were calculated from simultaneous observations on various stations. Thus two values are always obtained, whose mean ($\overline{\triangle g'}$) is taken as the measured gravity difference. $\omega = \Sigma \overline{\triangle g'} = -3.9 \times 10^{-2}$ mGal. was calculated to form the closing error of loop I. There are 14 measured differences which means that the correction *(k)* will be $+0.28 \cdot 10^{-2}$ mGal per difference.

TABLE 8

Loop II: The observations and their reduction.

Observation station	△ *b*	*T*	*L*	*g*″	r_h	*g*′
65 35 44	+48	8h56	80 61	7 496.7	+14.8	7 511.5
43	+43	9h01	77 78	7 233.5	+13.3	7 246.8
44	+48	06	80 67	7 502.3	+14.8	7 517.1
43	+43	10	77 85	7 240.1	+13.3	7 253.4
42	+42	16	85 29	7 932.0	+13.0	7 945.0
43	+43	22	77 86	7 241.0	+13.3	7 254.3
42	+42	27	85 31	7 933.8	+13.0	7 946.8
41	+35	33	82 77	7 697.6	+10.8	7 708.4
42	+42	39	85 35	7 937.6	+13.0	7 950.6
41	+35	45	82 82	7 702.3	+10.8	7 713.1
40	+38	50	76 22	7 088.5	+11.7	7 100.2
41	+35	54	82 84	7 704.1	+10.8	7 714.9
40	+38	59	76 25	7 091.3	+11.7	7 103.0
39	+ 6	10h05	73 35	6 821.6	+ 1.9	6 823.5
40	+38	10	76 27	7 093.1	+11.7	7 104.8
39	+ 6	16	73 39	6 825.3	+ 1.9	6 827.2
Stake A	—66	22	76 57	7 121.0	—20.4	7 100.6
39	+ 6	31	73 43	6 829.0	+ 1.9	6 830.9
A	—66	37	76 59	7 122.9	—20.4	7 102.5
B	—71	44	76 59	7 122.9	—21.9	7 101.0
A	—66	50	76 60	7 123.8	—20.4	7 103.4
B	—71	55	76 58	7 121.9	—21.9	7 100.0
C	—31	11h02	84 94	7 899.4	— 9.6	7 889.8
B	—71	10	76 61	7 124.7	—21.9	7 102.8
C	—31	16	85 01	7 905.9	— 9.6	7 896.3
65 35 81	+44	23	87 28	8 117.0	+13.6	8 130.6
C	—31	30	85 00	7 905.0	— 9.6	7 895.4
81	+44	35	87 28	8 117.0	+13.6	8 130.6

From the closing error one obtains the mean error *(m)* of one difference in loop I:

$$m = \frac{3.9}{\sqrt{14}} \cdot 10^{-2} = 1.0 \times 10^{-2} \text{ mGal}$$

Reduced gravity differences ($\overline{\triangle g}$) were calculated in the computing table.

Correspondingly loop II was computed in Appendix 2 and a closing error of —9.8 × 10^{-2} mGal obtained per nine differences, which gives as mean error

$$m = \frac{9.8}{\sqrt{9}} \cdot 10^{-2} = 3.3 \times 10^{-2} \text{ mGal.}$$

Control station sequence III

Control station sequence III begins from station 653 547 of loop I and contains 8 new control stations and stake-line stations measured in the same connection. Back and forth measuring only was carried out. The results are listed in Table 9. The total drift during the period of survey between 11^h 45—13^h 28 was 11 units. The drift was divided evenly between the readings of all the stations, because the difference in the observation times of all the stations was almost equal. The drift correction has been marked in the table with the letter *k* and the corrected reading with the letter *L'*. The gravity values reduced to the elevation of the station have been marked with the letter *g'*.

TABLE 9

Sequence III: Observations and their reduction.

Observation station	$\triangle h$	*T*	*L*	*k*	*L'*	*g''*	r_h	*g'*
653 547	+50	11^h45	9 377	0	9 377	8 720.6	+15.4	8 736.0
642 308	+47	53	8 659	— 1	8 658	8 051.9	+14.5	8 066.4
642 309	+38	12^h00	8 580	— 1	8 579	7 978.4	+11.7	7 990.1
642 310	+37	06	8 493	— 2	8 491	7 896.6	+11.4	7 908.0
653 609	+47	11	8 559	— 2	8 557	7 958.0	+14.5	7 972.5
653 608	+48	16	8 208	— 3	8 205	7 630.7	+14.8	7 645.5
653 607	+47	23	7 350	— 4	7 346	6 831.9	+14.5	6 846.4
653 606	+47	27	7 532	— 4	7 528	7 001.0	+14.5	7 015.5
653 605	+15	34	7 135	— 5	7 130	6 630.9	+ 4.6	6 635.5
y = 534.0 x=85.80	—25	43	7 509	— 5	7 504	6 978.7	— 7.7	6 971.0
y = 534.0 x=85.70	—60	45	7 703	— 6	7 697	7 158.2	—18.5	7 139.7
653 606	+47	51	7 534	— 7	7 527	7 000.1	+14.5	7 014.6
653 607	+47	58	7 352	— 7	7 345	6 830.9	+14.5	6 845.4
653 608	+48	13^h03	8 218	— 8	8 210	7 635.3	+14.8	7 650.1
653 609	+47	09	8 568	— 9	8 559	7 959.9	+11.4	7 971.3
652 309	+38	19	8 594	—10	8 584	7 983.1	+11.7	7 994.8
642 308	+47	23	8 670	—10	8 660	8 053.8	+14.5	8 068.3
653 547	+50	28	9 388	—11	9 377	8 720.6	+15.4	8 736.0

Tying measurements between the control stations and the stake-line stakes

The observations and results of the tying measurement have been compiled in Table 10. The tying always begins and ends at a control station so that the complete drift can be established from column *g''*. The drift corrected gravity value reduced to the height of the stake is in column *g* and the gravity difference calculated in relation to the control station is in column $\triangle g$.

TABLE 10

The gravity differences between the control stations and the stake-line stakes.

Observation station	△ *h*	*L*	*g″*	r_h	*g′*	*g*	△ *g*
653 540	+38	7 643	7 108.0	+11.7	7 119.7	7 119.4	0
K 152.00 *L* 51.80	—48	7 739	7 197.3	—14.8	7 182.5	7 182.5	+ 63.1
K 152.00 *L* 51.90	—51	7 735	7 193.6	—15.7	7 177.9	7 177.9	+ 58.5
K 152.00 *L* 52.00	—32	7 734	7 192.6	— 9.9	7 182.7	7 182.7	+ 63.3
653 540	+38	7 642	7 107.1	+11.7	7 118.8	7 119.4	0
x 79.20 *y* 531.00	—52	7 567	7 037.3	—16.0	7 021.3	7 021.3	— 98.1
x 79.10 *y* 531.00	—54	7 524	6 997.3	—16.7	6 980.6	6 980.6	—138.8
653 540	+38	7 643	7 108.0	+11.7	7 119.7	7 119.4	0
653 542	+42	8 555	7 956.2	+13.0	7 969.2	7 969.2	0
K 153.00 *L* 55.10	—71	8 655	8 049.2	—21.9	8 027.3	8 027.3	+ 58.1
K 153.00 *L* 55.20	—69	8 664	8 057.5	—21.3	8 036.2	8 036.2	+ 67.0
653 542	+42	8 555	7 956.2	+13.0	7 969.2	7 969.2	0
653 544	+48	8 094	7 527.4	+14.8	7 524.2	7 542.2	0
K 153.55 *L* 59.00	0	8 211	7 636.2	0	7 636.2	7 635.3	+ 93.1
K 153.50 *L* 59.00	—31	8 127	7 558.1	— 9.6	7 548.5	7 646.7	+104.5
653 544	+48	8 097	7 530.2	+14.8	7 545.0	7 542.2	0
653 545	+36	8 612	8 009.2	+11.1	8 020.3	8 020.3	0
K 154.00 *L* 60.80	—62	8 678	8 070.5	—19.1	8 051.4	8 051.1	+ 30.8
K 154.00 *L* 60.70	—54	8 600	7 998.0	—16.7	7 981.3	7 980.7	— 39.6
653 545	+36	8 613	8 010.0	+11.1	8 021.1	8 020.3	0
653 583	+45	8 129	7 560.0	+ 13.9	7 573.9	7 573.9	0
K 149.00 *L* 60.20	—40	8 157	7 586.0	—12.3	7 573.7	7 573.7	— 0.2
K 149.00 *L* 60.30	—55	8 099	7 532.1	—17.0	7 515.1	7 515.1	— 58.8
K 149.00 *L* 60.40	—65	8 127	7 558.1	—20.0	7 538.1	7 538.1	— 35.8
653 583	+45	8 125	7 556.3	+13.9	7 570.2	7 573.9	0

TABLE 10. (continued)

Observation station	△ h	L	g″	r_h	g′	g	△ g
653 584	+42	8 647	8 041.7	+13.0	8 054.7	8 054.7	0
K 149.00 L 62.40	—55	8 681	8 073.3	—17.0	8 056.3	8 056.1	+ 1.4
K 149.00 L 62.50	—55	8 699	8 090.1	—17.0	8 073.1	8 072.6	+ 17.9
653 584	+42	8 648	8 042.6	+13.0	8 055.6	8 054.6	0
653 581	+44	8 737	8 125.4	+13.6	8 139.0	8 139.0	0
K 152.00 L 58.30	—37	8 756	8 143.1	—11.4	8 131.7	8 131.0	— 8.0
K 152.50 L 58.40	—50	9 036	8 403.5	—15.4	8 388.1	8 384,5	+245.5
653 581	+44	8 732	8 120.8	+13.6	8 134.4	8 139.0	0

The calculation of gravity values for the control stations

The calculation of gravity values for the control stations was started from station 653 540 whose starting value was calculated with the aid of four stake-line stations. In Table 11 the original gravity values of the stake-line sations are g', the gravity difference for the control station obtained in the tying measurements $\triangle g$ and the gravity value for the control station 653 540 in the last column.

TABLE 11

The relative gravity value for control station 653 540 calculated from the stake-line stakes in the vicinity.

Stake-line station	g′	△ g	Station 653 540
K = 152.00 L = 51.80	3 192.2	— 63.1	3 129.1
K = 152.00 L = 51.90	3 182.3	— 58.5	3 123.8
K = 152.00 L = 52.00	3 184.1	— 63.3	3 120.8
x = 79.20 y = 531.00	3 020.6	+ 98.1	3 118.7
x = 79.10 y = 531.00	2 981.3	+138.8	3 120.1
		Mean	3 122.5
		Mean error	±1.9

A mean of 3 122.5 from five measurements was obtained for the gravity value of station 653 540. This coincides with the average gravity level of the stake-line stakes in the vicinity of the control station.

Furthermore, the gravity values of other control stations are obtained, beginning with this value, by using the reduced gravity differences $\overline{\triangle g}$ taken from Appendices 1 and 2. In Table 12, loop II has been calculated first and then loop I. The common station 653 544 has been used as starting station for both loops.

TABLE 12

The relative gravity values *(g)* of the stations of loops II and I.

Station	Δg ($P_n - P_{n-1}$)	g (10^{-2} mGal)	Station	Δg ($P_n - P_{n-1}$)	g (10^{-2} mGal)
Loop II:			*Loop I:*		
653 540	0	3 122.5	653 544	0	3 547.5
653 539	—278.9	2 843.6	653 545	+482.2	4 029.7
A	+272.5	3 116.1	653 546	+531.4	4 561.1
B	— 1.5	3 114.6	653 547	+ 71.0	4 632.1
C	+790.7	3 905.3	642 306	—358.1	4 274.0
653 581	+236.1	4 114.4	642 305	— 53.5	4 220.5
653 544	—593.9	3 547.5	642 304	—386.2	3 834.3
653 543	—266.0	3 281.5	653 587	—232.3	3 602.0
653 542	+692.6	3 974.1	653 586	+ 36.2	3 638.2
653 541	—239.0	3 735.1	653 585	+216.7	3 854.9
653 540	—612.6	3 122.5	653 584	+ 66.8	3 921.7
			653 583	—477.0	3 444.7
			653 582	+273.7	3 718.4
			653 581	+423.0	4 141.4
			653 544	—593.4	3 547.5

The gravity values of the stations of sequence III have been calculated (Table 13) in such a way, that from column g' of Table 9 the relative gravity of the stations has been computed as the average value of two measurements. The stations of the sequence have been given a reduction so that the gravity value obtained for its starting station 653 547 is equal to the gravity value obtained for this station with the aid of loop I.

TABLE 13

The relative gravity values *(g)* of the stations of Sequence III.

Station	Relative g	Plane reduction	Reduced g (10^{-2} mGal)
653 547	8 736.0	—4 102.9	4 632.1
642 308	8 067.3	»	3 963.4
642 309	7 992.5	»	3 888.6
642 310	7 908.0	»	3 804.1
653 609	7 971.9	»	3 869.0
653 608	7 647.8	»	3 544.9
653 607	6 845.9	»	2 742.0
653 606	7 015.1	»	2 911.2
653 605	6 635.5	»	2 531.6
x 85.80			
y 534.00	6 971.0	»	2 867.1
x 85.70			
y 534.00	7 139.7	»	3 035.8

The gravity values of the stake-line stakes calculated from the control stations, and their comparison with the results of the areal measurements

Above, the gravity values for the control stations were calculated so that at station 653 540 they coincided with that gravity plane which was used in the areal measurements. In the following, the gravity values g_1 of the stake-line stations employed in

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the comparison measurements, have been computed from the control stations by taking into consideration the difference $\triangle g$ obtained from the tying. The gravity value g_2 for the stake-line stations arrived at in the course of the actual areal survey has been taken from the calculation papers concerning the stake-line measurements of the sub-areas. If the value (g_1) obtained in the control station survey is considered correct, the difference $g_1 - g_2 = \triangle g_{1-2}$ gives an error with a unit of 10^{-2} mGal in the areal measurements. The results of the calculations are given in Table 14.

TABLE 14

The gravity differences between the control stations and the stake-line stakes.

Station	$\triangle g$	g_1	g_2		$\triangle g_{1-2}$
653 542		**3 974.1**			
K 153.00, *L* 55.10	+ 58.1	4 032.2	4 031.4		+ 0.8
K 153.00 *L* 55.20	+ 67.0	4 041.1	4 046.4		— 5.3
				Mean	— 2.3
653 544		**3 547.5**			
K 153.55 *L* 59.00	+ 93.1	3 640.6	3 644.0		— 3.4
K 153.50 *L* 59.10	+104.5	3 652.0	3 552.8		— 0.8
				Mean	— 2.1
653 545		**4 029.7**			
K 154.00 *L* 60.80	+ 30.8	4 060.5	4 053.6		+ 6.9
K 154.00 *L* 60.70	— 39.6	3 990.1	3 986.0		+ 4.1
				Mean	+ 5.5
653 581		**4 141.4**			
K 152.00 *L* 58.30	— 8.0	4 033.4	4 138.2		— 4.8
K 152.00 *L* 58.40	+245.5	4 386.9	4 386.6		+ 0.3
				Mean	— 2.3
653 583		**3 444.7**			
K 149.00 *L* 60.20	— 0.2	3 444.5	3 451.7		— 7.2
K 149.00 *L* 60.30	— 58.8	3 385.9	3 388.0		— 2.1
K 149.00 *L* 60.40	— 35.8	3 408.9	3 404.0		+ 4.9
				Mean	— 2.2
653 584		**3 921.7**			
K 149.00 *L* 62.40	+ 1.4	3 923.1	3 916.0		+ 7.1
K 149.00 *L* 62.50	+ 17.9	3 939.6	3 941.0		— 1.4
				Mean	+ 2.8
A		3 116.1	3 121.6		— 5.5
B		3 114.6	3 119.4		— 4.8
C		3 905.3	3 881.9		(+23.4)
653 605					
x 85.80 *y* 534.00		2 867.1	2 864.4		+ 2.7
x 85.70 *y* 534.00		3 035.8	3 021.8		(+14.0)
				Mean	+ 2.7

The examination of the results reveals that gravity differences ($\triangle g_{1-2}$) calculated in relation to different stake-line stakes from the same control stations vary rather much. The variation in many cases is noticeably greater than the accuracy of the stake-line measurement presupposes. This is caused by the fact that in the time between the stake-line observations and the control station measurements, which in some cases was almost 2 years, some of the stakes had been destroyed or knocked down from their original place. Later on these stakes were lifted up or replaced by new ones, so that they were no longer at the same elevation as the original ones.

In the tying measurements the stake-line stakes were not relevelled but the original elevations were used. The doubtful elevations of the stakes could not be checked afterwards either, because the crew had moved to other places of work. For this reason all stakes were considered of equal value by calculating an arithmetic average for $\triangle g_{1-2}$ in the vicinity of each control station. Exceptions are station C and stake $x = 85.70$, $y = 534.00$, whose result was disregarded as being obviously incorrect.

The deviations of the sub-areas from the plane of the control station net are given in Table 15.

TABLE 15

The deviations of the sub-areas from the plane of the control station net.

Control station	Sub-area	$\triangle g$ (10^{-2} mGal)
653 540	4/1964	+0
653 542	7/1964	—2.3
653 544	X/1965	—2.1
653 545	X/1965	+5.5
653 581	III/1965	—2.3
653 583	VIII/1965	—2.2
653 584	IX/1965	+2.8
A	3/1964	—5.5
B	6/1964	—4.8
653 605	7/1964	+2.7

According to the results of Table 15 there has been no actual drifting of the plane, rather the deviations are distributed on both sides of the chosen ideal plane roughly within the limits of an accuracy achieved in routine survey. The mean error computed from the square sum of the deviations is 3.4×10^{-2} mGal.

The example of Virtasalmi shows that the sub-area method employed based on the measurements of stake-lines can give thoroughly satisfactory results. However, whenever possible a separate base station net should be measured right at the start of the survey, so that the sub-areas could be tied to those stations as the measuring of the area proceeds.

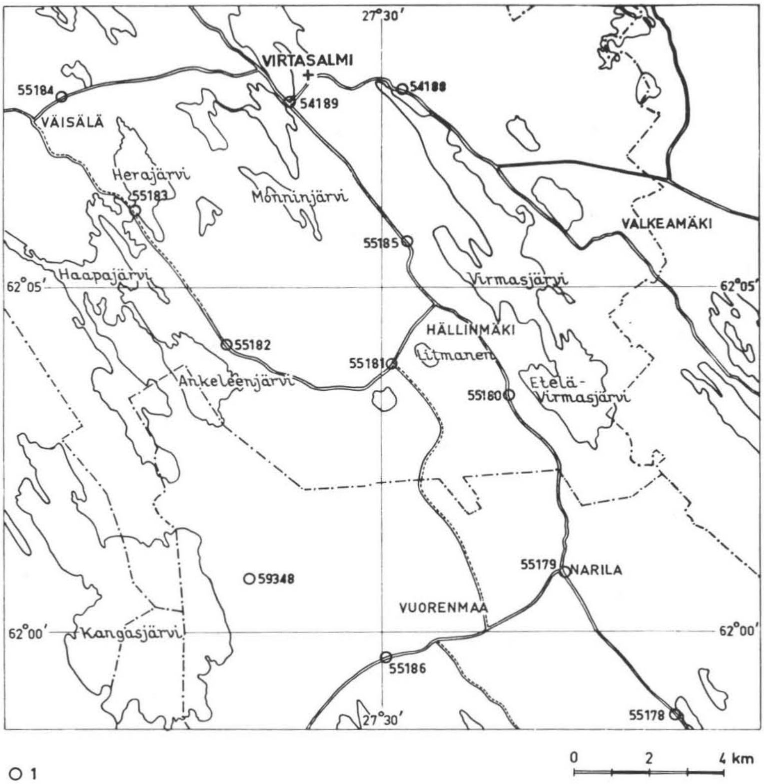

FIG. 14. The location of the gravity stations of the Geodetic Institute.

Tying to the gravity stations of the Geodetic Institute

The gravity values of the control stations in the absolute system

Five of the gravity stations measured by the Geodetic Institute in 1955 — stations 55 179, 55 180, 55 181, 55 182 ja 55 185 — are situated within the Virtasalmi exploration area (Fig. 14). The gravity observations were carried out at these stations with the Nörgaard gravimeter and the elevations determined with a barometer. The stations were not staked permanently, but a plan was drawn for each station showing the distances between the station and some fixed marks near-by.

In the summer of 1966 the Geological Survey determined the locations of these stations with the aid of the plans, levelled them and measured the gravity differences between them and the nearest station of the Geological Survey. The location of these stations were established in respect to the stake-line system of the Geological Survey.

Also station 54 073 at Pieksämäki railway station was connected with the observations of the Geological Survey by determining the gravity difference between stations 54 073 and 653 547. Table 16 lists the data given by the Geodetic Institute concerning its stations.

By measuring the gravity differences between the control stations of the Geological Survey and the stations of the Geodetic Institute it was possible to determine the gravity difference between these two systems. The results are compiled in Table 17.

The tying measurement gives 982 037.72 mGal as the value of the difference. This must be added to the relative gravity values of the Geological Survey to obtain the absolute values of the stations. The differences obtained at different stations deviate from the mean ±0.16 mGal, which is in agreement with the accuracy obtainable with the Nörgaard gravimeter.

TABLE 16

The coordinates and gravity values for the stations of the Geodetic Institute.

No	φ	λ	h	*g* (mGal)
54 073	62°18'.01	27°10'.10	121.6	982 075.6
55 179	62°00'.87	27°35'.50	144.6	982 066.8
55 180	62°03'.45	27°33'.85	124.4	982 077.2
55 181	62°03'.83	27°30'.25	112.7	982 077.8
55 182	62°04'.17	27°25'.30	116.6	982 075.2
55 185	62°05'.68	27°30'.70	128.4	982 077.0

TABLE 17

The results of the tying measuremets between the control stations of the Geological Survey and the gravity stations of the Geodetic Institute.

1	2	3	4	5	6	7
653 539—55 179	28.44	+0.48	28.92	982 066.8	982 037.88	+0.16
653 542—55 180	39.74	—0.14	39.60	982 077.2	982 037.60	—0.12
653 581—55 181	41.41	—1.14	40.27	982 077.8	982 037.53	—0.19
653 584—55 182	39.22	—1.91	37.31	982 075.2	982 037.89	+0.17
653 545—55 185	40.30	—0.87	39.43	982 077.0	982 037.57	—0.15
653 547—54 073	46.32	—8.60	37.72	982 075.6	982 037.88	+0.16
				Mean	982 037.72	
				Mean error	0.07	

1. Control station — a station of the Geodetic Institute.
2. Relative gravity in mGal at the control station (Geological Survey system).
3. Observed gravity difference in mGal.
4. Relative gravity at the station of the Geodetic Institute (Geological Survey system).
5. Absolute gravity at the station of the Geodetic Institute.
6. Difference between the absolute system and the system of the Geological Survey.
7. Deviations of the difference from the mean.

On the basis of the value calculated above for the difference, the following gravity values are obtained for the control stations of the Geological Survey as expressed in the system of the Geodetic Institute.

653 539	982 066.16	653 584	076.94
653 540	068.95	653 583	072.17
653 541	075.07	653 582	074.90
653 542	077.46	653 581	079.13
653 543	070.54	A	068.88
653 544	073.20	B	068.87
653 545	078.02	652 308	077.35
653 546	083.33	652 309	076.61
653 547	084.04	652 310	075.76
642 306	080.46	653 609	076.41
652 305	079.93	653 608	073.17
652 304	076.06	653 607	065.14
653 587	073.74	653 606	066.83
653 586	074.10	653 605	063.04
653 585	076.27		

The transformation of the relative gravity values of the Geological Survey into the Bouguer anomalies of the Geodetic Institute

The Bouguer anomalies ($\triangle g''$) of the Geodetic Institute have been computed by means of the following formula (Honkasalo 1962).

$$\triangle g'' = g + r_F - r_B - \gamma_0 \qquad (12)$$

where g = observed gravity
r_F = free-air reduction
r_B = Bouguer reduction
γ_0 = normal gravity

The free-air and Bouguer reduction have been combined in such a way that $r_F + r_B = 0.1965\ h$ mGal/m, in which case *(12)* becomes

$$\triangle g'' = g + 0.1965\ h - \gamma_0 \qquad (13)$$

The relative Bouguer values (g_B) of the Geological Survey have been calculated from the formula

$$g_B = g_S + 0.2000\ h' + r\varphi \qquad (14)$$

where g_S = relative gravity at the station
h' = observed elevation of the Geological Survey $h' = h - 31.55$
$r\varphi$ = latitude correction

$$r\varphi = (\gamma_1 - \gamma_0) + 5.00 \qquad (15)$$

where γ_1 = the normal gravity at a chosen base station
γ_0 = the normal gravity at an observation station
5.00 = the correction value in mGal, given to the base station

Formula *(14)* becomes thus

$$g_B = g_S + 0.2000\,(h - 31.55) + \gamma_1 - \gamma_0 + 5.00 \qquad (16)$$

The transference correction is obtained from formulas *(13)* and *(16)*

$$\triangle g'' - g_B = g + 0.1965\ h - \gamma_0 - g_S - 0.2000\,h + 0.2000 \cdot 31.55$$
$$- \gamma_1 + \gamma_0 - 5.00$$

$$\triangle g'' - g_B = g - g_S - 0.0035\,h + 6.31 - \gamma_1 - 5.00 \qquad (17)$$

where $g - g_S$ = 982 037.72 i.e. the transference correction between the relative gravity values of the Geological Survey and the values of the Geodetic Institute.
γ_1 = 982 077.85, which is the normal gravity at the base station

Inserting these numerical values into the above equations one obtains

$$\triangle g'' - g_B = -38.82 - 0.0035\,h \tag{18}$$

Thus, the correction is not constant but includes a factor depending on the elevation, h, of the station. This is caused by the difference existing between the values of the combined free-air and Bouguer corrections in both systems. If h is replaced by the mean elevation of the exploration area $h = 130$ m we obtain $0.0035 \times h = 0.45$ mGal. In this case the greatest variations in elevation $\pm$ 25 m induce a maximum error of $\pm$ 0.08 mGal to the transference correction even if the deviation of the elevation at the stations from the mean elevation were omitted. The transference correction is now

$$\triangle g'' = g_B - 39.27 \text{ mGal} \tag{19}$$

According to equation *(19)* the Bouguer anomalies of the Geodetic Institute are obtained by subtracting 39.27 mGal from the relative Bouguer values of the Geological Survey.

When doing transference calculations it is important to note that only the last three digits of the Bouguer values have been included in the gravity maps and computations of the Geological Survey. Consequently 50.00 mGal has to be added to the numbers 200—999. Thus, e.g. number 653 = 56.53 mGal. As a unit 0.01 mGal has been employed. Accordingly, number 1 000 equals 60.00 mGal. When a number exceeds 1 000, only the three last digits have been taken into account.

ON THE INTERPRETATION OF THE GRAVITY ANOMALIES

General

The gravity anomalies are caused by inhomogeneity in the distribution of masses, the so-called anomalous masses, in the earth's crust. If we denote the gravity anomaly with $\triangle g$, the volume of the anomalous mass with V, the density difference in regard to surroundings with δ and the location of the anomalous mass with A we obtain a symbolic equation

$$\triangle g = f(V;\ \delta;\ A) \tag{20}$$

The quantity A depends not only on the distance of the anomalous mass from the observation point but it is also governed by the shape and attitude of the mass.

By the interpretation of a gravity anomaly we understand the solution of the above equation, i.e. the determination of the density distribution as accurately as possible in terms of the gravity anomaly. A perfect interpretation is impossible without some restrictions, because there is an infinite number of mass distributions which can produce a given gravity anomaly.

According to Jung (1961, p 206) it is possible, without any restriction, to determine unambiguously the following quantities based on the observed gravity anomaly:

— total mass i.e. the extra mass in regard to surroundings
— centre of gravity of the anomalous mass
— the so-called ideal disturbance layer *(die ideelle störende Schicht)*

The total mass permits the calculation of ore tonnage provided the density of the ore and country rocks is known. Werner (1965) has computed ore reserves of the Stora Sahavaara and the Leveäniemi iron ore deposits in North Sweden on the basis of the observed gravity anomalies. For the Stora Sahavaara, which is a magnetite deposit, the tonnage has also been estimated from the magnetic anomaly. Both estimates agree well with the results obtained by diamond drilling.

At Leveäniemi only the gravity anomaly, whose magnitude is about 8.5 mGal, gives an estimate compatible with the real ore reserves. This is caused by the fact that the Leveäniemi deposit is only weakly magnetic containing in addition to magnetite also hematite and martite.

While emphasising the significance of gravity observations in the exploration for iron ores Werner (1961) states that the advantage of gravity measurements over magnetic observations lies in the fact that the density and iron content of an ore are more closely correlated than the magnetization of ore and its iron tenor.

Bott and Smith (1958) have derived inequalities which permit the computation of the greatest possible distance between the upper surface of an anomalous mass of an arbitrary shape and the observation plane. The determination of this limit depth is carried out with the aid of parameters whose values depend upon the shape of the gravity anomaly.

The depth of a point mass (the centre of gravity of a homogenous spherical mass) and a horizontal line mass (the axis of a homogeneous and horizontal cylinder) can also be calculated from a gravity anomaly. The forementioned mathematical solutions are not always geologically sensible due to the fact that an observed gravity anomaly is caused by the total effect of all the anomalous masses near-by. The geological interpretation should be carried out in such a way that every anomalous mass connected with a certain geologic body could be explained separately based on the observed anomaly. In this case it is important that the effects of the different anomalous masses on the total anomaly can be estimated at least approximately.

In exploration, gravity measurements are seldom used alone. Generally they are connected with other observations obtained by magnetic or electric methods, or by geological field work carried out in the same area. The interpreter has thus at his disposal results given by various methods which he combines and compares with each other in order to find out a geological model best corresponding to the anomaly. It depends on the experience and ability of the interpreter how closely his model approaches reality.

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The gravity anomaly of a given mass

It can be shown that an anomalous mass of an arbitrary shape at a point x, y, z causes a gravity anomaly ($\triangle g$) at another point x_1, y_1, z_1 the magnitude of which has the form:

$$\Delta g = k \cdot \delta \int\int\int \frac{(z - z_1)\ dx \cdot dy \cdot dz}{[(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2]\ 3/2}, \quad (21)$$

where k = the gravitational constant

δ = the density difference between the anomalous mass and its surroundings

The application of this general integral even to relatively simple geometric bodies causes difficulties. Many text-books of applied geophysics give formulas derived for the anomalous masses of spherical and ellipsoidal shape. In addition there are equations for a gravity anomaly at a point situated in the axis of a vertical cylinder and a truncated cone. Parasnis (1961) has derived formulas for a gravity anomaly at an arbitrary point outside a circular plate and a vertical cylinder. Talwani and Ewing (1960), Goguel (1961), Collette (1965) and Kolbenhayer (1966) have proposed methods for calculating the gravity anomalies produced by three-dimensional bodies of an arbitrary shape. According to them the body is divided into thin polygonal slabs in horizontal or vertical direction, the effect of each slab being computed separately.

In practice the geologic model can often be replaced with sufficient accuracy by a two-dimensional body which extends infinitely in one direction and whose cross-sectional area remains constant along the whole length of the body.

Various sector-diagrams or maps have been constructed for the graphical solution of a gravity anomaly by the given mass of three- and two-dimensional bodies.

Vertical diagrams have been presented e.g. by Lindblad and Malmquist (1938), Jung (1961) and Collette (1965). In general, they have been calculated on the basis of a density difference of 1 g/cm^3. The values can easily be converted into the required density difference (δ) by multiplying the value by δ.

Anomaly curves have also been computed for bodies of different shapes. A comprehensive selection of curves is included in the publication edited by the Russian geophysicist Mikov (1955).

On the gravity anomalies of the rocks and ores

The densities of common rocks vary from 2.50 to 3.20 g/cm^3. Table 18 lists the densities of some of the most common igneous rocks and crystalline schists given by Reich (1960, pp. 11—12).

TABLE 18

The densities of common rocks according to Reich (1960).

Rock type	density g/cm²	range
IGNEOUS ROCKS		
Granite	2.65	2.56—2.74
Syenite	2.74	2.60—2.95
Diorite	2.86	2.72—2.99
Gabbro	3.00	2.89—3.09
Peridotite	3.06	2.78—3.37
Dunite	3.22	2.93—3.34
CRYSTALLINE SCHISTS		
Quartzite	2.68	2.63—2.91
Mica schist	2.73	2.54—2.97
Phyllite	2.74	2.68—2.80
Limestone	2.78	2.63—2.87
Chlorite schist	2.87	2.75—2.98
Amphibolite	3.00	2.91—3.04
Gneiss, depending on composition		2.59—3.00

Depending on the composition of a rock, the densities can vary within one and the same rock type as much as 0.2—0.5 g/cm³. Especially some heavy minerals such as garnets and accessory ore minerals cause a noticable change in the density of a rock.

The difference in density between various rocks may be 0.1—0.7 g/cm³. Since the magnitude of a gravity anomaly depends on the excess mass, which is a product of the volume and the density difference, it is obvious that a rock with great volume can produce gravity anomalies with a magnitude of tens of milligals. The gradient in the deepest parts of these anomalies may often reach values of 5—10 mGal per kilometre.

The densities of the ore minerals are conspicuously higher than those of the general rock forming silicates.

TABLE 19

The densities of the most common ore minerals according to Reich (1960).

Ore mineral	Density g/cm³
Sphalerite	3.9—4.2
Chalcopyrite	4.1—4.3
Pyrrhotite	4.5—4.6
Pyrite	4.9—5.2
Magnetite	4.9—5.2
Hematite	4.9—5.2
Arsenopyrite	6.0—6.2
Galena	7.3—7.6

Table 19, which has been compiled on the basis of Reich's data, gives the densities of the most common ore minerals.

Due to the high density of the ore minerals, the density difference between the compact ores and their surroundings is, in general, at least 1 g/cm³, in some cases even 3—4 g/cm³, whereas the disseminated ores may contain economic amounts of metals without having materially changed the density of the host rock. For example 10 % chalcopyrite changes the density of a rock only 0.10—0.15 g/cm³ depending on the original density.

In spite of the fact that the density difference between a compact ore and its environment is remarkable, the gravity anomalies produced by the ores are much smaller than the rock anomalies due to the limited size of the ore bodies. One of the strongest ore anomalies measured in Finland is the gravity anomaly of the Pyhäsalmi pyrite deposit. The maximum value of the anomaly is 3 mGal with a density difference of 1.6 g/cm³ (Laurila *et al*, 1962). An anomaly produced by an ore body is visualized in Fig. 15. The figure comprises a set of anomaly curves which have been computed on the basis of a vertical ore plate whose width is 20 metres, length infinite and the lower surface 200 metres beneath the observation plane. The density difference of the ore as regards the environment is 1.0 g/cm³. The curves have been calculated for the different depths of the upper surface of the ore body.

Curve (0) represents a case in which the upper surface of the ore body touches the surface of the ground. The maximum anomaly of the ore body is 1.07 mGal. The anomaly decreases rapidly towards the sides reaching the half-value ($\triangle g$ max/2) about 30 metres from the mid-line of the ore. At a distance of 100 metres from the ore the anomaly is only 0.2 mGal.

The maximum value of the anomaly decreases rather rapidly with the increasing distance between the upper surface of the ore body and the measuring plane. If the depth is 10 metres (curve 1) the maximum anomaly is 0.75 mGal, and if the depth is 50 metres (curve 5) the anomaly has been reduced to 0.37 mGal. The horizontal gradient of the anomaly also decreases with the increasing depth, with the consequence that the anomaly becomes difficult to distinguish e.g. from the gravity »noise» caused by the variation of the thickness in overburden.

Since the anomaly decreases rapidly outside the ore body the spacing between the observation stations must be narrow and the measuring lines arranged in such a way that they cut the strike of the ore body as perpendicularly as possible.

Regional and local anomaly in exploration

A regional anomaly is generally thought to have been produced by the density differences existing under the granitic layer of the earth's crust, whereas the local anomalies have been caused by an inhomogeneous distribution of masses near the earth's surface. The areas surveyed gravimetrically in ore exploration are so small that the above division becomes inappropriate. In ore exploration a regional anomaly is considered to be an anomaly produced by a formation larger than an ore body

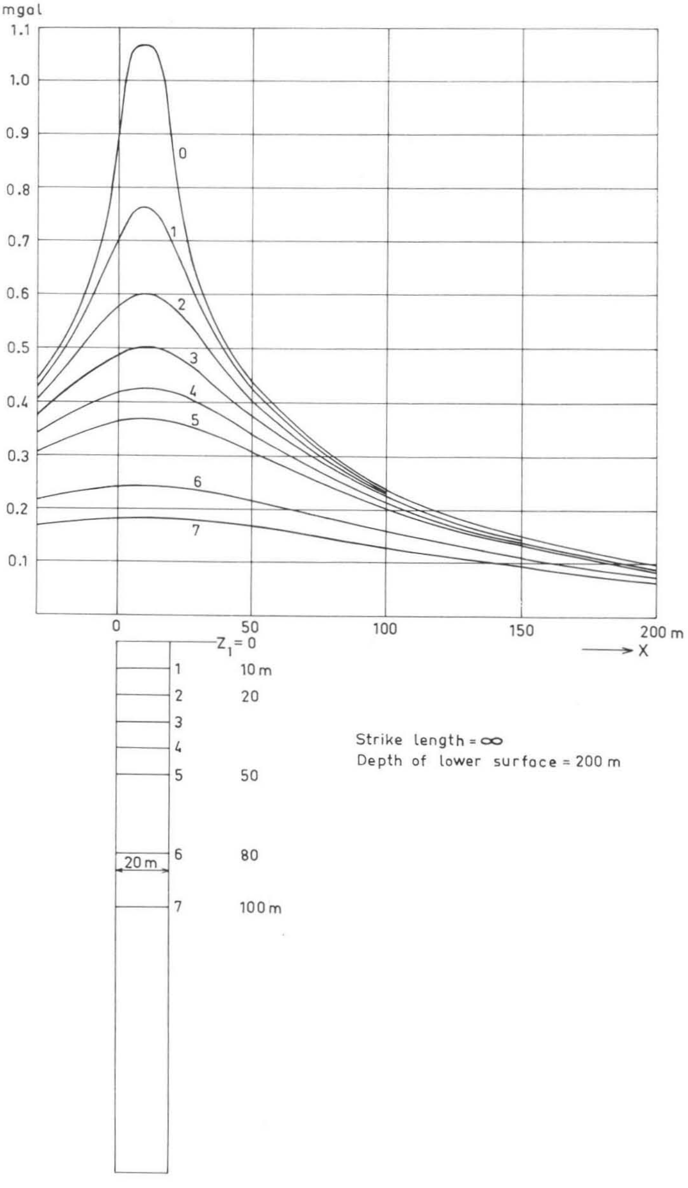


FIG. 15. The gravity anomaly caused by a vertical, sheet-like ore according to Lindblad and Malmqvist (1938). The width of the ore is 20 metres and its lower surface 200 m below the ground level. The density difference between the ore and the surroundings is assumed to be $1 g/cm^3$. The gravity anomaly curves are calculated for the different depths of the upper surface of the ore from the ground level.

or any deposit under investigation. Under these conditions the regional anomaly has only a very relative meaning entirely depending on the object of the investigation. Thus, e.g. a gravity anomaly caused by the different densities of two large rock bodies represents a regional anomaly, whereas an ore body situated in the contact between them is recognised as a local anomaly. A joint anomaly produced by a rock contact and an ore body is called a total anomaly. A residual anomaly is a local anomaly which is obtained by subtracting the regional anomaly from the total anomaly. Thus, the determination of a residual anomaly requires the elimination of the regional anomaly.

The elimination of regional anomaly and the calculation of residual anomaly

The effect of an ore body on the total anomaly can be small or the regional anomaly may completely overshadow it. In the latter case the ore anomaly can, however, be obtained by eliminating the local anomaly from the regional anomaly, as the present author has shown in his study concerning the Kemi chromite deposit (Siikarla 1962). Even if the anomaly produced by the ore body or rock under investigation is recognisable, the anomaly can be clarified and more details obtained if the regional anomaly is eliminated (Siikarla 1964).

Since the mass distribution producing a regional anomaly is generally unknown, it is impossible to eliminate the regional anomaly with purely mathematical methods. Consequently, the determination of a regional anomaly is to a great extent conventional. Different elimination methods have been given by Griffin (1949), Grosse (1957), Jung (1961) and Laurila *et al.* (1962).

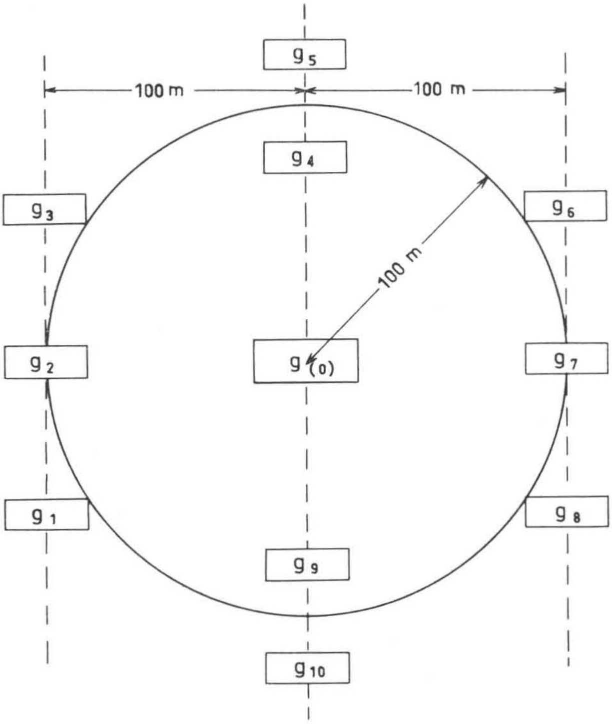
The calculation of the residual anomalies in the Virtasalmi area was based on the Griffin method according to which the residual anomaly is obtained from the formula

$$\triangle g = g\,(0) - \bar{g}\,(r) \qquad (22)$$

where $g(0)$ is the observed gravity (the total anomaly), and $\bar{g}(r)$ the regional gravity (regional anomaly) at the station (0).

$$\bar{g}(r) = \frac{1}{2\pi} \int_0^{2\pi} g(r\,;\,\alpha)\ \mathrm{d}\alpha \qquad (23)$$

Thus, the gravity in the circumference of a circle with a radius r and centre at (0), is, according to the definition, the regional anomaly at point (0). Its value was computed with the aid of a template similar to that presented in Fig. 16 and which differs from those usually employed in such a way that the stations used for the calculation of $g(r)$ are not all located regularly along the circumference of the same circle. To ease the computation involved, the stations were chosen so that the holes in the



$$\Delta g = g(0) - \frac{(g_1 + g_2 + g_3 + \cdots + g_{10})}{10}$$

FIG. 16. The template employed for the calculation of the residual anomalies at Virtasalmi.

template coinside with the observation stations on the map, in which case the numerical g-values were obtained directly without interpolation.

In the Virtasalmi region the residual anomalies were calculated for an area of 18 km^2. Residual anomaly was computed at every observation station within this area, begining with the relative Bouguer values.

On the joint interpretation of the geophysical and geological observations

Apart from the gravity survey, other geophysical measurements are also frequently conducted in an area under exploration, the most common of which are magnetic and electromagnetic observations. The purpose of the magnetic survey is to distinguish from each other the geological formations whose effects on the earth's magnetic field are high enough to render it measurable with the devices available. Electromagnetic measurements are employed for the localisation of electrically conducting bodies within the bedrock.

The interpreter has thus at his disposal results given by different geophysical methods, whose mutual comparison allows him to distinguish geological formations from each other also in the case when one of the physical properties, e.g., density, is the same but either magnetic or electric properties differ.

The prerequisite for the interpretation is that the physical properties of the rocks existing in the area are known. The necessary physical parameters, such as density, magnetic properties and electric conductivity are measured on the outcrops or diamond drill cores.

A geologist working in the area under consideration usually provides the geophysicist with the necessary samples whose rock type has been established and which can be used for routine determinations. The geologist also supplies information concerning the location of the outcrops, their rock types and tectonic data.

Since the geological interpretation of the geophysical observations generally proceeds slowly and becomes more accurate with the increasing geological information, it is crucial for the success of the interpretation that the geophysicist and the geologist cooperate during the whole period of exploration.

THE PRINCIPAL FEATURES OF THE GEOLOGY AND THE PHYSICAL PROPERTIES OF THE MAIN ROCK TYPES OF THE VIRTASALMI AREA

Geology

The bedrock of the Virtasalmi area (Map 4) is composed of supracrustal rocks, including amphibolites, limestones, different kinds of gneisses and plutonic rocks. The composition of the latter varies from peridotites to trondhjemites.

According to Hyvärinen's geological investigations (to be published in the near future) the supracrustal rocks form zones, many kilometres in length, mainly in a NW direction. Part of these zones approach one other in the southern part of the area near the Narila junction, forming an extensive arc opening towards the NW, and encircling a plutonic massif.

In general, the supracrustal rocks have been strongly metamorphosed, with the consequence that the original structures are seldom recognisable. The strike of the schistosity follows the shapes of the schist zones, thus varying in different parts of the area. The dip is generally steep, 70°—80° or even vertical.

The supracrustal rocks form, in a way, a continous series whose members are connected with each other through intercalates. Stratigraphically the mica gneisses appear to underlie the amphibolites. The upper part of the mica gneiss is often characterized by amphibolite and quartz-feldspar gneiss intercalates. Similarly, in the lower part of the amphibolite mica gneiss and quartz-feldspar gneiss layers occur. The latter can attain widths of many tens of metres in places. This contact zone is further characterized by limestone intercalates, which occasionally reach considerable dimensions.

The amphibolite is mainly diopside amphibolite, which, in all likelihood, was originally marl. During the deposition of the marl, volcanic activity has also taken place, for the diopside amphibolite contains thin intercalates of uralite-plagioclase porphyrite or hornblende amphibolite. The tuffitic features are still recognisable in the latter.

According to Hyvärinen's results the plutonic rocks form a synorogenic differentiation series beginning with peridotites and gabbros and grading into diorites, quartz diorites, granodiorites and trondhjemites. The aplite and pegmatite dykes, met with in the area, penetrate both the supracrustal and the plutonic rocks.

Quartz diorite is the most common plutonic rock, but diorite also occurs fairly often, whereas granodiorite and trondhjemite are encountered only occasionally. The extensive plutonic massifs are characterized by an abundance of schist xenoliths in places.

There are only a few peridotites in the area. Gabbros are met with more often and they seem to occur at the margins of the quartz diorite massifs or near them in the schist zones.

The physical properties of the main rock types

For the interpretation of the geophysical anomalies, the density and magnetism were determined from the main rock types occuring in the area. The measurements were carried out mainly by using the samples collected in the years 1964 and 1965 either from the outcrops or from the drill cores. The samples available do not represent the whole area, for the mapping of the NW part of the area was not completed until the summer of 1966. As far as the rocks of the last mentioned area are concerned it has only been possible to make qualitative estimations about their physical properties by comparing the rock types in the outcrops with the observed geophysical anomalies.

The density determinations were performed by weighing the samples in air and in water and using the equipment described earlier by the author (Siikarla, 1962).

The magnetism of the rock types was determined by measuring their susceptibility with the American »Magnetic Susceptibility Bridge» equipment. The remanent magnetism, possibly incorporated with the rocks, was not determined.

Conductivity measurements were performed only on some copper ore samples from Hällinmäki.

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The density of the rock types

The densities of the samples taken from the 59 outcrops of the area are listed in Table 20. Due to the limited number of these samples, some rock types being represented by only 1—4 specimens, 876 density determinations were made from the drill cores of the Hällinmäki copper deposit. The measurement comprised the cores of six holes, a total length of 744 metres. The density distribution was determined for the whole length of each drill hole and the individual measurements were based on a piece of core about 60—80 cm in length.

The average densities of the rocks were obtained by calculating the weighed averages from the density distributions of four holes, viz. holes Nos. 3, 4, 5 and 22, and by taking the rock contacts as the limits of calculation.

The weighed average was computed as follows:

Let the lengths of the measured samples be

$$l_1, \; l_2, \; \ldots\ldots\ldots\ldots\ldots\ldots \; l_n$$

and the corresponding densities

$$\delta_1, \; \delta_2, \; \ldots\ldots\ldots\ldots\ldots\ldots \; \delta_n$$

Then the weighed average ($\overline{\delta}$) is

$$\overline{\delta} = \frac{l_1 \cdot \delta_1 + l_2 \cdot \delta_2 + \ldots\ldots\ldots \; l_n \cdot \delta_n}{\sum\limits_{1}^{n} l} \qquad (24)$$

TABLE 20

Densities of outcrop samples in the Virtasalmi area.

Rock type	Density g/cm²	Range	Number of determinations
Garnet skarn [1])	3.35	—	1
Diopside amphibolite	3.03	2.97—3.08	3
Hornblende amphibolite ...	3.01	2.91—3.11	19
Diopside gneiss	3.01	2.82—3.14	3
Hornblende gneiss	2.91	2.88—2.91	3
Mica gneiss	2.74	2.65—2.82	10
Veined gneiss	2.67	2.66—2.68	3
Peridotite	3.19	3.17—3.20	4
Gabbro	2.94	2.90—2.97	3
Diorite	2.85	2.77—2.95	3
Quartz diorite	2.74	2.68—2.79	6
Granodiorite	2.69	—	1

[1]) Diopside amphibolite very rich in garnet

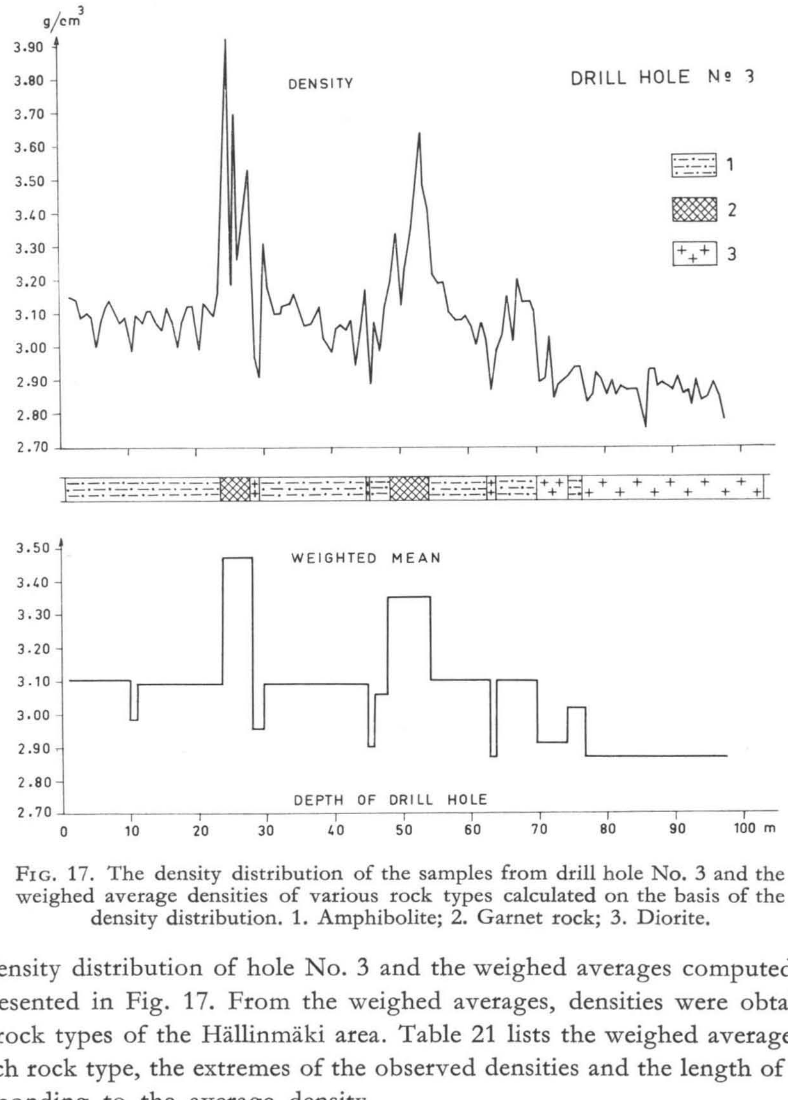

FIG. 17. The density distribution of the samples from drill hole No. 3 and the weighed average densities of various rock types calculated on the basis of the density distribution. 1. Amphibolite; 2. Garnet rock; 3. Diorite.

The density distribution of hole No. 3 and the weighed averages computed from it are presented in Fig. 17. From the weighed averages, densities were obtained for some rock types of the Hällinmäki area. Table 21 lists the weighed average density for each rock type, the extremes of the observed densities and the length of the core corresponding to the average density.

The large deviation in the density of the supracrustal rocks given in Table 21 is conspicuous. This is due to the great geological variations near the ore body at Hällinmäki. Diopside amphibolite contains in places variable amounts of garnet, which increases the density to well over average. In some other places diopside amphibolite and hornblende amphibolite occur as relatively thin layers alternating with each other, in which case the hornblende amphibolite layers in diopside amphibolite reduce the density of the latter. Also the narrow pegmatite veins have a similar effect upon the density of the amphibolites.

TABLE 21

Densities obtained from the drill cores of Hällimäki.

Rock type	Dnsity g/cm²	Range	Length m
Garnet skarn	3.37	3.13—3.92	34
Diopside amphibolite [1]) ...	3.08	2.98—3.21	77
Hornblende amphibolite [1])	2.85	2.71—3.05	67
Limestone	2.73	2.61—2.91	49
Gabbro	2.94	2.86—3.02	18
Diorite	2.89	2.78—2.94	49

[1]) Strongly migmatized

The density of the garnet-bearing skarn depends on the amount of garnet and ore minerals present.

The density of the pure limestone varies from 2.72 to 2.74 g/cm³. The densities noticeably higher than the average are due to the amphibolite intercalates.

At Hällinmäki the densities of the plutonic rocks show less variation than those of the supracrustal rocks.

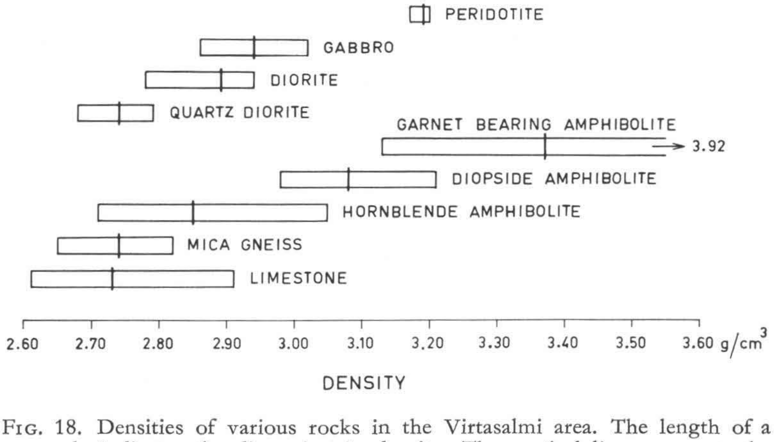

FIG. 18. Densities of various rocks in the Virtasalmi area. The length of a rectangle indicates the dispersion in density. The vertical line represents the average density.

The results of the density determinations listed in Tables 20 and 21 are compiled in Fig, 18. Taking into consideration the dispersion in the density values it is seen that the supracrustal rocks form a gapless series, in which the highest density values of the lighter rock always overlap the lowest values of the next heavier type. For limestone, mica gneiss and hornblende amphibolite the overlapping is so complete that the average density of one rock type falls well within the area of dispersion of the other type. Diopside amphibolite and garnet-bearing skarn rock are, in this respect, easier to distinguish from the other rocks.

TABLE 22

Distribution of rocks into density classes.

Density g/cm³	Rock type
> 3.20	Garnet skarns
3.20—3.00	Peridotites and diopside amphibolites
3.00—2.80	Gabbros, hornblende amphibolites and diorites
2.80—2.60	Mica gneisses, limestones, quartz diorites and granodiorites

The densities of quartz diorite, diorite and gabbro fall within the density area of the three lightest supracrustal rocks, whereas the density of the peridotite is situated between the densities of the two heaviest supracrustal rock types. On the basis of the average densities, the rock types of the Virtasalmi area can be roughly divided into the density classes presented in Table 22.

The magnetic properties of the rock types

The study of the magnetic properties of the rock types was based mainly on the samples collected from the outcrops. A great many susceptibility measurements were made from the cores of the Hällinmäki deposit, but the application of these results to the rest of the area is, however, difficult, since magnetite has been formed obviously in association with the ore formation. Magnetite occurs as small lenses or disseminations in various rocks connected with the ore body.

No limestone outcrops have been detected in the area. Consequently the susceptibility measurements were made from the cores of the holes drilled between Lake Luomanen and Tervalampi.

The magnetic properties of the rock types are discussed in the following.

Amphibolites

The samples, totalling 22, include diopside and hornblende amphibolites. The observed susceptibility values vary from $74 \cdot 10^{-6}$ to $9\,700 \cdot 10^{-6}$ cgs. Roughly a half of the measured values fall within the range $74—116 \cdot 10^{-6}$ cgs. The values arranged into four classes are presented in Table 23.

TABLE 23

Susceptibility of amphibolite samples.

Class	Average 10^{-6}cgs	Range 10^{-6}cgs	Number of samples
I	87	74—116	13
II	268	239—297	2
III	794	578—1 228	3
IV	7 294	4 384—9 700	4

The amphibolites of the different classes are distributed areally so that the most strongly magnetic types (classes III and IV) belong to the extensive amphibolite arc whose western half runs north of the Narila junction through the Litmanen pond towards the NNW. The eastern half runs via the centre of Lake Virmasjärvi roughly northwards.

The less magnetic types (classes I and II) are all connected with the amphibolite formations situated outside this arc. The major part of the samples belonging to these classes was taken from the amphibolites occuring on the eastern shore of Lake Virmasjärvi at Särsälänniemi.

If the observed magnetic anomalies are compared with amphibolite outcrops, it can be concluded that the magnetic anomalies of 1 000—4 000γ in magnitude are associated with the forementioned amphibolite arc, whereas the amphibolites on the eastern shore of Lake Virmasjärvi are connected with anomalies less than 1 000γ in magnitude. Also the amphibolites encountered in the SW part of the area are characterized by relatively weak anomalies.

Gneisses

The gneiss samples include mica gneisses and veined gneisses as well as hornblende and diopside gneisses. 17 samples from the total of 19 samples were only weakly magnetic with an average susceptibility of $41 \cdot 10^{-6}$ cgs. The extreme values were $12 \cdot 10^{-6}$ and $104 \cdot 10^{-6}$ cgs, respectively. Two samples gave values $389 \cdot 10^{-6}$ and $587 \cdot 10^{-6}$ cgs.

Consequently the gneisses are not generally associated with the magnetic anomalies excluding some pyrrhotite- and graphite-bearing zones where the magnetic anomalies may reach values as high as 8 000γ.

Limestones

No limestone outcrops were encountered. Susceptibility measurements were made on the cores of drill holes Nos. 1, 2 and 105 and the results are listed in Table 24.

The susceptibility of the limestones, which, by visual estimation, are very pure, is $4—6 \cdot 10^{-6}$ cgs.

Many samples, especially those from hole No. 2, contain abundant serpentine bands, which, however, do not seem to affect the magnetic properties of the rock. The limestones do not cause magnetic anomalies.

TABLE 24

Susceptibility of limestone samples.

Hole No	Depth interval	Average 10^{-6}cgs	Range 10^{-6}cgs	Number of samples
1	195.80—198.25	4	4— 4	5
2	43.30— 83.85	12	4—30	32
105	209.95—217.60	15	6—20	7

TABLE 25

Susceptibility of diorite samples.

Class	Average 10^{-6}cgs	Range 10^{-6}cgs	Number of samples
I	40	19—80	14
II	349	174—759	5
III	2 706	1 649—4 054	7

Diorites

A total of 26 diorite samples was collected from the outcrops and most of them belong to the massif encircled by the large amphibolite arc. The observed values of susceptibility vary from $19 \cdot 10^{-6}$ cgs to $4\,054 \cdot 10^{-6}$ cgs. In Table 25 the measured samples have been divided into three classes according to their magnetic properties.

The areal distribution of the diorites is characterized by the same feature as that of the amphibolites. Strongly magnetic rocks (class III) are all associated with the massif inside the amphibolite arc. According to L. Hyvärinen the massif contains abundant amphibolite xenoliths in places. The weakly magnetic diorites are situated outside the arc.

Gabbros and peridotites

Only 7 samples were obtained from gabbros and peridotites. They are all from the eastern side of Lake Virmasjärvi. The obtained susceptibility values vary from $66—434 \cdot 10^{-6}$ cgs, with an average of $175 \cdot 10^{-6}$ cgs. Gabbros and peridotites are extremely weakly magnetic, which shows that they are free from magnetite. This holds true over a rather extensive area, since no magnetic anomalies are associated with the gabbro and peridotite outcrops on the W and N side of Lake Ankeleenjärvi. This is also valid for the Näärinki—Pekurila area, about 20 kilometres to the SSE of Narila.

Conclusion

The susceptibility values of the rock samples are depicted graphically in Fig. 19. Every rock type, or in case a rock type has been divided into classes, every class, has been presented with a rectangle which covers the variation in susceptibility of the rock in question. The average of the susceptibility has been marked with a short vertical line. The numbers inside the rectangles reveal what per cent of the samples of this rock type fall within the area of the rectangle.

If the samples are classified according to the average susceptibility, 60 % of them fall within the range $1—100 \cdot 10^{-6}$ cgs, i.e. all the limestones, 89 % of the gneisses, the amphibolite class I and 54 % of the diorites. 31 % of the samples fall within the

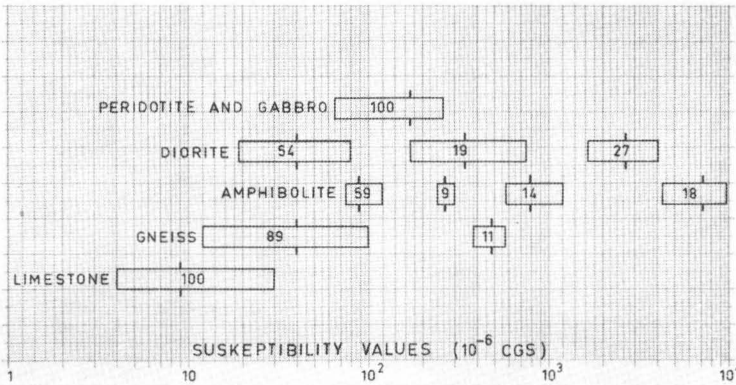

FIG. 19. Susceptibilities of various rocks in the Virtasalmi area plotted on a logarithmic scale. The length of a rectangle indicates the variation in susceptibility and the vertical line its average. The number inside the rectangle shows the percentage of the samples falling within the area of the rectangle.

range of 100—1 000 $\cdot 10^{-6}$ cgs. That is, gabbros and peridotites, 19 % of the diorites, the amphibolite classes II and III, which together represent 23 % of the total of amphibolite samples, and 11 % of the gneisses.

Only 9 % of the samples belong to the range 1 000—10 000 $\cdot 10^{-6}$ cgs, which is the most important range as far as the magnetic anomalies are concerned. These samples are amphibolite and diorite.

About 550 susceptibility determinations were made from the cores of Hällinmäki. They represent, however, a rather limited area. At Hällinmäki the susceptibility of gabbro varies from 35 to 90 $\cdot 10^{-6}$ cgs and that of the pure diorite from 30 to 100 $\cdot 10^{-6}$ cgs. The susceptibility of the diorites containing amphibolite xenoliths may reach values as high as 2 400—4 000 $\cdot 10^{-6}$ cgs.

The variation of the magnetism in amphibolites at Hällinmäki is larger than that of the outcrop samples. In general, the highest values vary from 6 000 to 10 000 $\cdot 10^{-6}$ cgs, but occasionally the susceptibility may rise even as high as 100 000 $\cdot 10^{-6}$ cgs.

What has been said above concerns only induced magnetism. No studies have been carried out on the remanent magnetism which may possibly exist in the rocks. Neither has its effect upon the magnetic anomalies been established so far.

The electric conductivity of the rock types

No systematic measurements of conductivity were carried out either on the rocks or the ores of the Virtasalmi area. At an early stage of the drilling at Hällinmäki, a number of specific resistance determinations were performed from the cores containing ore minerals.

It was possible to carry out qualitative estimations in various parts of the area by comparing the outcrops and drill holes with the indications obtained by means of the electromagnetic survey. Graphite-, pyrrhotite- and pyrite-bearing mica gneisses form fairly large and coherent conducting zones. Also amphibolites and garnet-bearing skarns occasionally contain sulphides in such quantities, that they appear as conductors in the electromagnetic survey. Further, some fracture and displacement zones behave as conductors especially when measured by the Turam techniques. The conductivity of these fracture zones is mainly due to the electrolyte-bearing ground water.

THE GEOLOGICAL INTERPRETATION BY MEANS OF PHYSICAL PROPERTIES

The aim of the interpretation in the Virtasalmi area

The primary purpose of the geophysical investigation carried out in the Virtasalmi area was to localise the ore deposits which might exist there. In addition, the aim was to obtain as much information as possible concerning the general geology of the area by means of a geophysical survey. This included:

— The determination of the dimensions of the rock types encountered in the outcrops and the investigation of the contacts.
— The identification of these rocks in areas where no outcrops are detectable by means of the geophysical anomalies.
— The discovery of new rock types with the aid of the geophysical anomalies.
— The determination of the strike and dip of the schists.
— The directing of the geological mapping, the search for ore boulders and excavation into the geologically critical areas.

Some general viewpoints concerning the interpretation

It depends on the physical properties of the rocks, their mode of occurrence and structure, to what extent the rock types can be distinguished from each other geophysically. In general, the physical properties are heterogeneously distributed in rocks. This is caused by the variation in the mutual amounts of minerals, by the accessory minerals and by the fact that another rock type occurs as xenoliths, veins or thin intercalates in it. The physical properties of the rocks in a certain area usually form a continuous series, in which the extreme values of the rocks, whose physical properties are close to each other, overlap. This holds true for example in the Virtasalmi area as far as the densities and the magnetic properties of the rocks are concerned (cf. Figs. 18 and 19). Under these circumstances only rocks differing sufficiently from each other on the basis of their physical properties can be distinguished by

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means of one geophysical method alone. By employing several methods simultaneously the geophysical resolution can be increased, since e.g. rocks with similar densities may have different magnetic or electric properties. By taking into consideration the effect of the structure of the rock upon the anomaly patterns and the possible stratigraphic and tectonic observations, the accuracy of the interpretation can be improved still further.

The mode of interpretation in the Virtasalmi area

The interpretation is based on the physical properties of the rocks and the information obtained from the outcrops and drill holes concerning the relationship between the rocks and the anomalies. The detailed comparison between the rock types and anomalies was made mainly using maps drawn with a scale of 1 : 2 000. For the accurate location of the most important outcrops, the outcrops were tied to the stake lines used for the geophysical measurements. An intensified search for outcrops was concentrated upon the parts of the area which, according to geophysical observations, were critical from the point of view of interpretation. At some of these points the bedrock was exposed by excavations if the overburden was shallow enough. For the excavations, the most shallow points of the overburden were located within the area of magnetic and electromagnetic anomalies by means of the so-called »Metal Locator» which is an electromagnetic device with a working frequency of about 100 kHz.

The preliminary interpretation, based on the forementioned physical properties of the rocks, was performed in the Virtasalmi area employing the following principles.

The heaviest rocks, amphibolites, peridotites and gabbros occur on the gravity maps in the anomalies which are positive with regard to the other rocks. The distinction of amphibolites from peridotites and gabbros is possible by means of a magnetic map since the amphibolites are mainly connected with the positive magnetic anomalies, while the peridotites and gabbros are magnetically neutral. Also the shapes of the anomalies were used to draw a distinction between the schists and the plutonic rocks.

The type of anomaly associated with the schists is on a whole longish, its length far exceeding its width. The contours restricting the anomaly are parallel to each other and also to the strike of the schists. The separate maxima associated with the anomaly follow the same direction. In addition to schists, also narrow plutonic intrusives may cause anomalies of similar shape due to the fact that they have intruded conformably into the schists.

The general features of the anomalies caused by the large homogeneous plutonic bodies are noticeably rounded. The contours form a set of nearly concentric rings approaching circles in shape. In spite of the fact that the anomalies produced by the plutonic rocks seldom show as simple a pattern, it is characteristic of them that the contours do not prefer any particular direction.

When diorites occur together with amphibolites they produce negative gravity anomalies with regard to their environments. Should the diorites be surrounded by gneisses, attempts should be made to distinguish the diorites from the gneisses mainly by the shape of the anomaly.

The pyrrhotite- and graphite-bearing gneisses do not show any features on the gravity map which could be used to distinguish them clearly from the other gneisses and diorites. On the other hand, they can be identified by means of the magnetic and electromagnetic anomalies.

The densities of the limestones are very close to those of the mica gneisses. However, the largest limestone zones are indicated on the gravity map by the negative anomaly zones. This is obviously due to the fact that the upper surface of the limestone has been weathered. On the magnetic maps the limestones are situated in areas slightly negative with regard to the chosen base level.

THE GEOPHYSICAL ANOMALIES AND GEOLOGY OF THE VIRTASALMI AREA

Presentation of the results of the geophysical measurements

The geophysical observations were presented at first by means of maps drawn on transparent sheets with a scale of 1 : 2 000, each sheet covering an area of 1 sq. km. Using a photographic technique these maps were joined together to form maps with scales of 1 : 10 000 and 1 : 20 000.

The relative Bouguer values were presented on the gravity maps by means of contours, with intervals of 0.1 mGal.

On the magnetic maps the anomalies of the vertical component were presented with contours indicating the variation of the magnetic field in comparison with an arbitrary base level. The contours were drawn with the following intervals: 250γ, 500γ, $1\ 000\gamma$, $2\ 000\gamma$, $4\ 000\gamma$, etc. The contours form a geometric series.

The results of the electromagnetic Slingram measurements were depicted as imaginary and real component maps. The Turam observations were presented as contour maps showing the measured phase differences and the reduced amplitude ratios.

All the maps were drawn in accordance with the map sheet division based on the Gauss-Krüger coordination.

The appended geophysical maps have a scale of 1 : 50 000. Due to the change in scale it has been necessary to simplify the maps considerably so that the general presentation of the area lacks some of the detailed data seen in the original larger scaled maps. The simplification is most prominent in the presentation of the results of the magnetic and Slingram measurements. The magnetic map (Map 1) shows the anomalies whose intensity is $1\ 000\gamma$ or more. The real component anomalies indicating the conducting zones on the electromagnetic Slingram map (Map 2) are presented with lines running through the maxima of the anomalies. Thus the lines show only the location and the length of the conducting zone but do not give any indication as to the intensity and width of the Slingram anomaly. The presentation of the gravity map (Map 3) is as detailed as possible. In comparison with the original maps only every second contour was drawn, with the consequence that the contour interval is 0.2 mGal.

The Hällinmäki copper deposit

The Hällinmäki copper deposit is situated 600—700 metres from the Juva—Virtasalmi road on its western side about 3 km to the SE of the Ankele junction. The geology of the deposit is well known due to drilling, and consequently it is the key to the interpretation of the rest of the area.

In the autumn of 1964 L. Hyvärinen found a small amphibolite outcrop containing chalcopyrite on the top of a hill covered with forest. Since this outcrop was associated with a positive gravity anomaly about 900 metres in length, whose two separate maxima were further characterised by a Slingram anomaly, indicating the presence of conducting material, drilling was started. A total of 87 holes was drilled in an area of about 400 × 700 metres. The drilling revealed a copper deposit whose exploitation was started in the autumn of 1966 by the Outokumpu Co.

According to Kahma (1965) the Hällinmäki copper ore is located in the SW margin of a carbonate and skarn formation, 700—800 metres in length and 200—250 metres in width, which is surrounded and brecciated by diorites. The strike of the formation is N50°—60°W and the dip 65°—75° N30°E. In the SW part of the formation there is mainly diopside amphibolite. The centre is characterized by hornblende amphibolite and the limestone occurs in the NE part of the formation. The mineralized parts of the diopside amphibolite contain so much garnet in places that it has been called garnet rock.

The most important ore minerals are chalcopyrite, pyrrhotite, pyrite, cubanite and magnetite.

The Bouguer anomalies of the Hällinmäki area are presented in Fig. 20 by means of contours, with 0.1 mGal as a contour interval. In this context, Bouguer anomaly means the variations of the relative Bouguer values and not the difference between the Bouguer value and the normal gravity calculated according to the international gravity formula.

On the map a rather large positive anomaly area is discernible restricted by the 950-contour. A longish zone running in a N 60°W direction occurs to the NE of stake line *K* 152.000 on one side of the area. This zone has three separate maxima (A, B and C), where the Bouguer values rise up to 1 000, i.e., 0.5—0.6 mGal above the environment. The area bounded by the 980 contour corresponds roughly to the Hällinmäki skarn formation investigated by means of drilling.

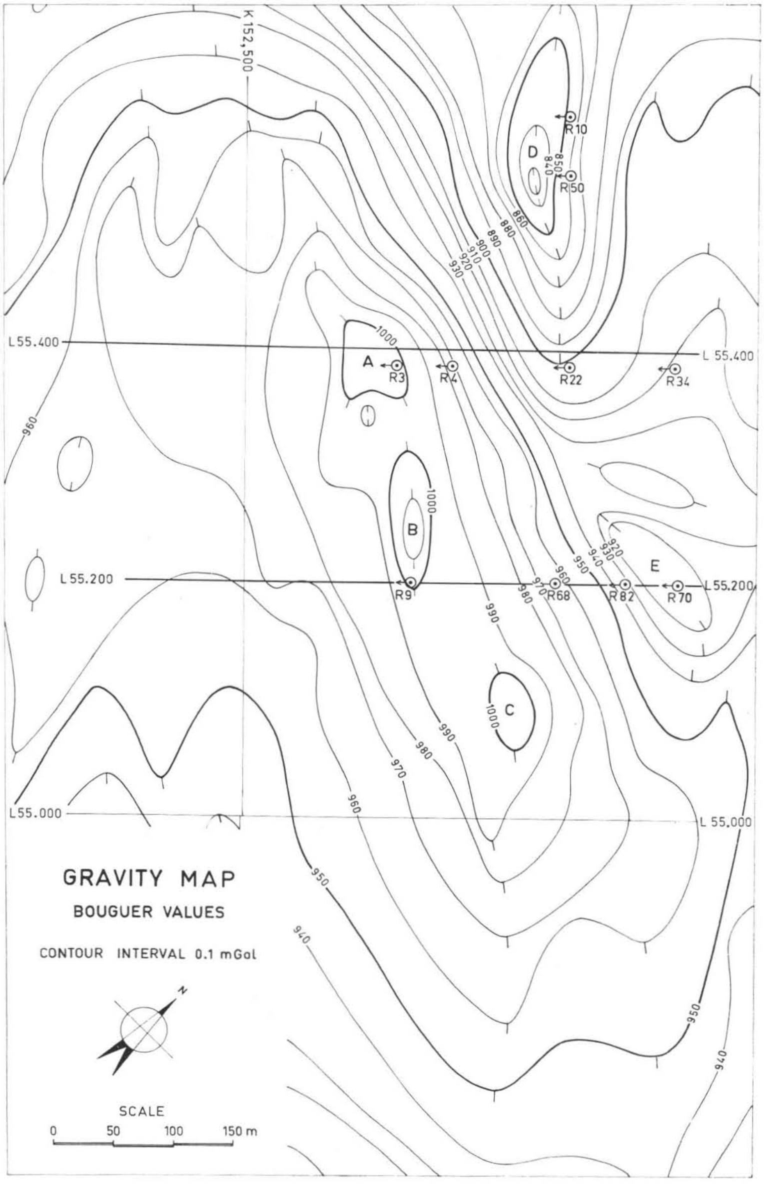

FIG. 20. The Bouguer anomalies at Hällinmäki.

About 200 metres north of the anomaly maximum (A) there is a very distinct negative anomaly (D), where the Bouguer values reach a minimum of 830. An attempt was made to pierce through the negative anomaly with drill hole No. 10. At first,

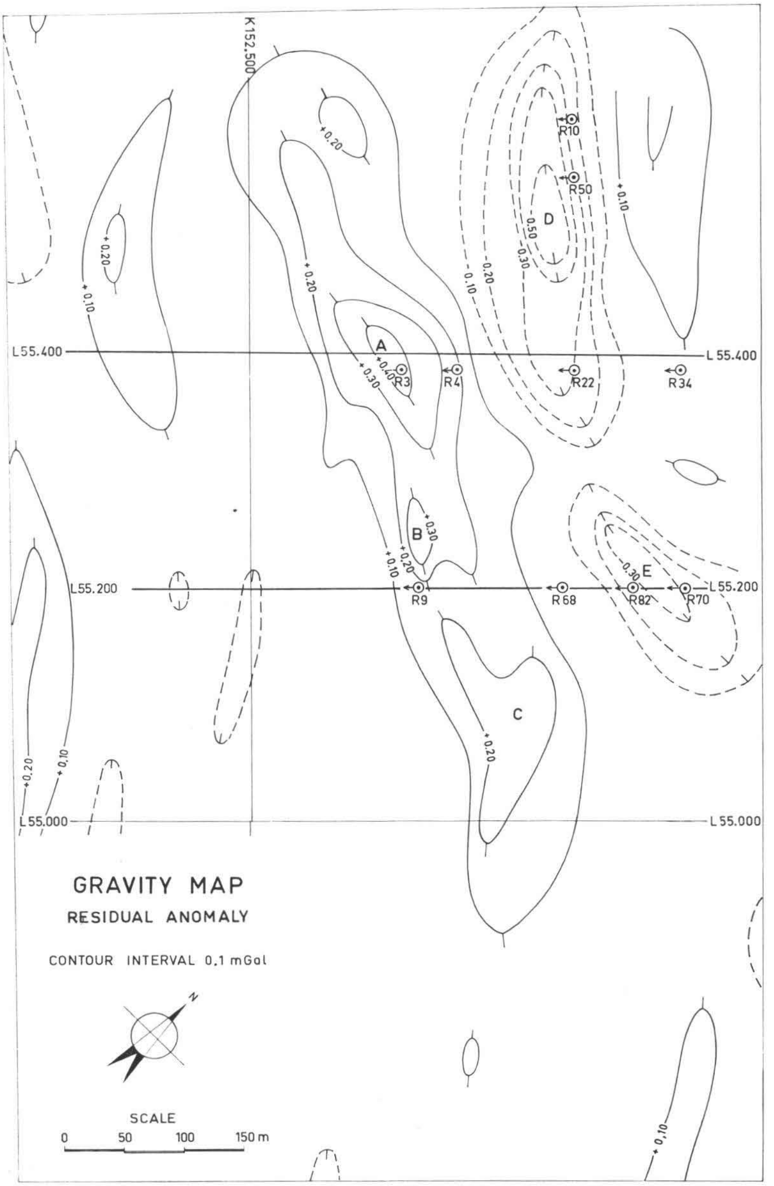

FIG. 21. The residual anomalies at Hällinmäki.

at a depth of 11 metres from the surface, a fractured quartz diorite was encountered after which preglacial weathering products were encountered which prevented further drilling. Another hole, No. 50, was drilled into the same anomaly. The overburden and weathered rock continued down to a depth of 53 metres from the surface. This was followed by pegmatite and very strongly fractured hornblende amphibolite.

Since the anomaly is part of a long electromagnetic Turam indication, it is apparent that the negative gravity anomaly is caused by a fracture zone, which furthermore has weathered intensively. A weaker negative gravity anomaly E and the anomalies NE of the anomaly D, which are, however, outside the area of this map sheet, also belong to this same system.

The residual anomalies presented in Fig. 21 were also calculated for the Hällinmäki area. On the map the positive anomaly, 750 metres in length, is due to the Karsikumpu skarn-amphibolite zone. Further, it has three separate maxima corresponding to anomalies A, B and C of the Bouguer map. The residual anomaly is strongest at A, where it is 0.40 mGal. Also the negative anomalies corresponding to D and E are very distinctive.

A more detailed picture of the correlation between gravity anomalies and geology is provided by two sections *L* 55.400 and *L* 55.200 (Figs. 22 and 23). The location of the sections and part of the holes drilled in them are marked in the Bouguer and residual anomaly map. The sections run in a SW—NE direction.

A vertical section 55.400 (Fig. 22) shows the Bouguer and residual anomalies as also the rock types to such an extent that it has been possible to construct the geological picture on the basis of the information gathered from the 8 holes situated in the profile. The rock types have been presented as slightly simplified down to a depth of about 150 metres, even though some of the holes have reached depths noticeably deeper than that. The gravity anomalies and the geology do not represent exactly the same section, since the holes were drilled along coordinate line *L* 55.385, whereas the gravity observations were carried out along line *L* 55.400. In practice this has hardly any effect since the transition of 15 metres is almost parallel to the strike of the rocks. In the section the profile of the surface and the thickness of the overburden have also been drawn. The latter is known exactly only at the site of the drill holes.

At first on the left (SW) the geologic picture shows diorite whose density is 2.87 g/cm^3. Then follows mineralised diopside amphibolite which occasionally contains garnet rock. The average density of the whole mineralised zone is 3.15 g/cm^3 according to the determinations made from hole No. 3. To the right (NE) of the ore zone there is diopside amphibolite first of all, with a density of 3.10 g/cm^3, and in addition intercalating hornblende and diopside amphibolite, which also include narrow diorite intrusions. The density determinations based on the core of hole No. 22 indicate that the average density of the migmatitic hornblende amphibolites is 2.86 g/cm^3. NE of the amphibolite zone, limestones are encountered whose density is 2.73 g/cm^3. Limestones are followed by a formation where amphibolites and diorites. alternate. The garnet rock is the heaviest rock in the section, its density being on an average 3.37 g/cm^3. However, the relative amount of the garnet rock is so small, if all the rocks are taken into consideration, that it is hardly seen in the anomaly pattern.

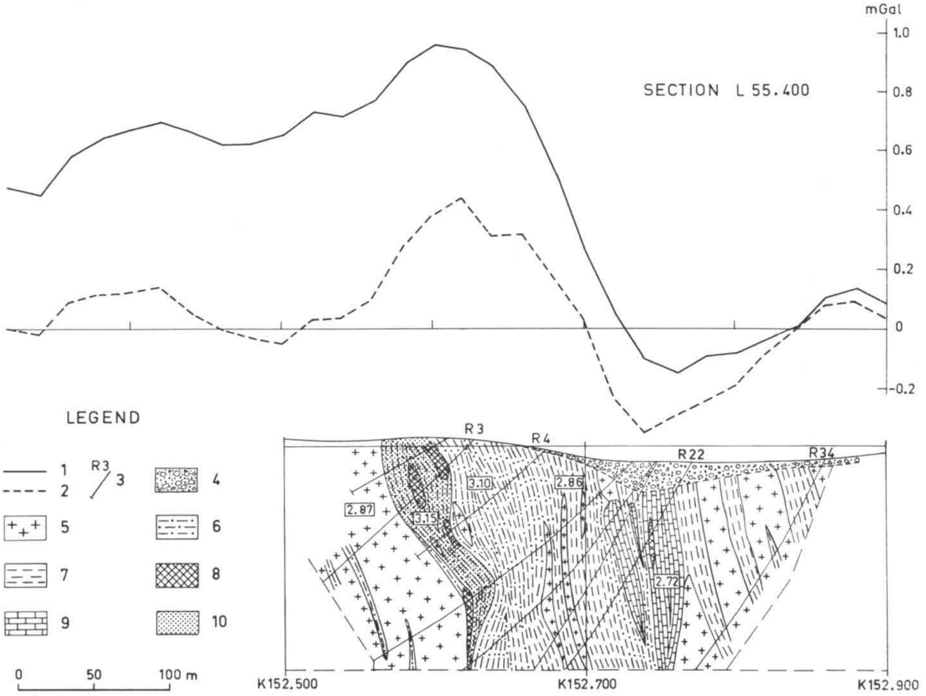

FIG. 22. Section L 55.400. The gravity anomalies and geology. 1. Bouguer anomaly; 2. Residual anomaly; 3. Drill hole; 4. Overburden; 5. Diorite; 6. Diopside amphibolite; 7. Hornblende amphibolite; 8. Garnet rock; 9. Limestone; 10. Ore. The average densities have been marked in the geological section.

The positive gravity anomaly is mainly due to the excess mass of diopside amphibolites. The maximum value of the anomaly and the centre of the anomalous mass are situated near the NE contact of the ore-bearing amphibolite.

The negative anomaly on the limestone is due to the fact that the density of the limestone is smaller than that of its surroundings, and also because there is a thick layer of overburden on the top of the limestone. Some parts of the overburden may also contain weathered surficial layers of limestone. Further, it reflects the effect of a large negative anomaly (D) visible on the Bouguer map (Fig. 21).

The general level of gravity on the SW side of the skarn deposit is about 0.4 mGal higher than on the NE side. This is mainly caused by the extensive amphibolite zone situated SW of the Hällinmäki deposit.

Section L 55.200 (Fig. 23) is located 200 metres SE of the former. The gravity anomaly is broader, more gently sloping and without such a distinct maximum as in section L 55.400.

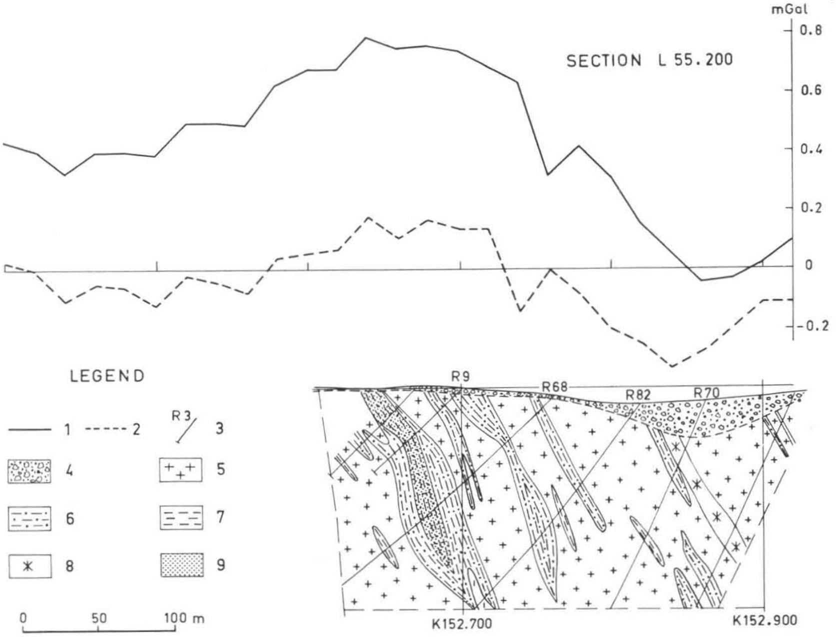

FIG. 23. Section *L* 55.200. The gravity anomalies and geology. 1. Bouguer anomaly; 2. Residual anomaly; 3. Drill hole; 4. Overburden; 5. Diorite; 6. Diopside amphibolite; 7. Hornblende amphibolite; 8. Pegmatite: 9. Ore.

The change in type of anomaly corresponds well with the change in geologic setting. The coherent amphibolite zone in section *L* 55.400 is replaced by several narrow amphibolite zones which are separated from each other by diorites. Consequently, as a whole the section is fairly rich in diorite. The negative gravity anomaly at the NE end of the section corresponds to the (E) anomaly on the Bouguer map. It is due to a fracture zone containing light pegmatitic rocks, and also to the overburden which here is thicker than in the environment.

There is a prominent correlation between the gravity anomalies of the Hällinmäki copper deposit and the areal geology. The whole positive gravity anomaly is caused by the diopside amphibolites and the garnet rocks associated with them being heavier than their surroundings. The amplitude of the anomaly is governed mainly by the total width of the skarn formation while its gradient depends on whether the skarn formation is coherent or broken by diorites.

The separate gravity maxima (A, B and C) indicate that mineralized skarn rock does not occur as a single body along the whole length of the deposit but it is broken by diorite intrusives.

The mutual correlation between the rock types and geophysical anomalies of the area

In the following the correlation between the various rock types in Virtasalmi and the geophysical anomalies is described, beginning with the supracrustal rocks and finishing with the plutonic rocks. Although the original interpretation started as is usual with the geophysical anomalies and ended with the rock types which cause them, this order of presentation had to be discarded for descriptive reasons. The description of the rock formations and their areal distribution is based on the appended geological map (Map 4) drawn up by L. Hyvärinen who was responsible for the geological exploration in the Virtasalmi area. The geological map has been somewhat simplified by omitting some small occurrences and the outcrop markings. Also part of the tectonic symbols have been left out. The naming of the geological formation has been carried out using the geographical names of the geological map.

In the following interpretation it has been necessary to refer to some structural features and details of the geophysical anomalies which were available on larger scaled maps, but which can no longer be shown on the appended maps with a scale of 1 : 50 000.

Amphibolites

The Vuorenmaa amphibolite in the southwest of the geological map is a part of the more extensive amphibolite sequence which continues to the south. Magnetic anomalies, which only sporadically exceed 1 000γ, are associated with the formation. There are also some weak conductors in the area, which are apparently connected with the mica gneiss xenoliths in the amphibolite. The amphibolite is outside the gravity map. The influence of the east and north contacts can be seen, however, right in the southwest corner of the gravity map, where the gravity begins to increase to the southwest, when it is decreasing in this direction in the surroundings.

The bipartite amphibolite occurrence to the east and northeast of the former is clearly visible on the gravity map as a positive anomaly. The occurrence cannot be restricted with the aid of magnetic anomalies. Several sharp magnetic anomalies as well as electric conductors are joined to the NE contact of the northern amphibolite. When these were drilled through, a weak pyrrhotite and pyrite dissemination was encountered, as well as some compact pyrrhotite veins, a few centimetres in width.

The amphibolite fold on the western side of Tervalampi which opens out to the SSE appears on the gravity map as a clear positive anomaly. Magnetic anomalies are associated with both sides of the fold. The rock type cannot be restricted by means of these anomalies, since corresponding anomalies also associate with the surrounding gneisses. The electric conductivity is caused partly by the layers of graphite in the mica gneiss inside the fold and partly by the pyrrhotite veins connected to the amphibolites. The amphibolite has been restricted by relatively frequent outcrops and a gravity anomaly.

On the SE side of Tervalampi there is a small amphibolite body which has been restricted on the basis of the gravity map. It has no outcrops. Amphibolite has only been established in a drill hole at the SW tip of the occurrence.

The chief amphibolite sequence of the area is clearly visible on the gravity and magnetic maps, Its western fork begins on the northern side of the Narila junction and runs west of Hällinmäki through the Litmanen pond to the northwest. It is also typical of this sequence that almost no Slingram indications are associated with it. Gravity and magnetic anomalies show that this amphibolite sequence is bipartite to the SSE of the Litmanen pond. Between these amphibolites, there is a relatively narrow gneiss zone which appears on the magnetic map as a conspiciously anomaly-free area. No outcrops were encountered but gneiss was established in two drill holes.

On the gravity map there is a narrow zone, about 3 kilometres in length, to the NW of the Narila junction, where the gravity is lower than in its surroundings. The same area appears on the magnetic map as magnetically weaker than its surroundings. This represents a diorite intrusion remaining inside the amphibolite as has been confirmed from the outcrops in the southern part of the anomaly in question.

About 1.5 km to the northwest of the Litmanen pond there is a marked break in the positive gravity anomaly. Immediately on both sides of this break there are abundant amphibolite outcrops. The break is probably caused by gneisses, since at its northeast end there is a quartz-feldspar gneiss outcrop. From the break to the NW the amphibolite formation has been constructed on the map solely on the basis of geophysical anomalies, since the first amphibolite outcrops are not encountered before the eastern side of the southern end of Lake Monninjärvi. According to the gravity map, it seems that the amphibolite sequence continues uninterrupted from the forementioned break for a least 1.5 km to the NNW. Also the magnetic anomalies continue up to here, in type the same as in the southern part of the sequence. From here to the NW, to the eastern side of Lake Monninjärvi, the gravity anomalies continue considerably more weakly. The magnetic anomalies remain under 1 000γ, while the value of the earth's magnetic vertical component keeps very constant over the whole area. Thus it is quite possible that this part of the amphibolite formation is not as coherent as is marked on the geological map, but may contain diorite abundantly and possibly also gneisses.

The eastern fork of the forementioned amphibolite sequence curves about 1 km nort of the Narila junction northeastwards to the southern end of Lake Virmasjärvi. From there it continues under Lake Virmasjärvi northwestwards according to the magnetic map and some outcrops established on the small islands of Lake Virmasjärvi. At Karhuniemi the sequence appears in several outcrops. According to the magnetic map this sequence continues from Karhuniemi on under Lake Virmasjärvi for about 3 km to the NNE and turns back from there to the SSE. On the northern side of Särsälänniemi the amphibolite sequence appears to turn to the NE running through the centre of Lake Valkeajärvi again in a northeastern direction. From Karhuniemi onwards the continuation of the sequence is based almost entirely on the magnetic map, since there is only one outcrop on an island on Lake Virmasjärvi and a second outcrop between Lake Virmasjärvi and Lake Valkeajärvi.

With the aid of gravity anomalies this sequence can be followed only from the northern side of the Narila junction to the southern end of Lake Virmasjärvi and at Karhuniemi. Elsewhere gravity observations are lacking.

On the eastern shore of Lake Virmasjärvi at Särsälänniemi there are abundant amphibolite outcrops whose associated magnetic anomalies are extremely weak and scattered. On the basis of the gravity observations it is difficult to say whether or not they belong to the Karhuniemi amphibolites because gravity measurements could not be carried out in the 200—300 metre wide strait between them.

An outcrop observation made on one of the islands near the southern end of Lake Virmasjärvi as well as electromagnetic measurements suggest that at least in the southern part and at the southern end of the lake there should be two separate amphibolite zones, between which there is a narrow gneiss horizon rich in graphite and sulphides. The easternmost of these amphibolites can be established again in several exposures on the eastern side of the Narila junction. In the same area there are very weak positive gravity anomalies.

Gneisses

Mica gneisses containing pyrrhotite and graphite are best recognised from the magnetic and electromagnetic maps. On the magnetic maps they usually form long uninterrupted anomaly zones, in which the intensity of the anomalies exceeds 1 000γ. On the electromagnetic maps they form outstanding conducting zones. The amount of sulphides is generally so small that it has no effect on the gravity anomalies.

The graphite gneiss sequence, running from the Narila junction to the northern side of Lake Tervalampi and continuing from the SW side of Lake Luomanen to the southern part of Lake Ankeleenjärvi, shows up particularly strongly on the geophysical maps. A continuous magnetic anomaly and many electric conductors are associated with this sequence. On the southwestern side of Lake Luomanen a roundish and gently sloping gravity anomaly is connected with this gneiss horizon. The strongest maximum of the gravity anomaly is situated outside the magnetic anomalies. The anomaly as a whole has been interpreted as caused by the plutonic rocks which have penetrated into the gneiss.

A second graphite gneiss sequence also begins from the Narila junction. It runs to the northeast of the former via the eastern part of Lake Luomanen to the NW. About 1.5 km to the northwest of Lake Luomanen it turns strongly westwards and continues to the northern side of Lake Ankeleenjärvi where it again turns northwest. This sequence can also be seen very clearly on the magnetic and electromagnetic maps. The southern part of the sequence between Lake Luomanen and the Narila junction is distinguishable as a zone of outstanding conductivity. The magnetic anomalies are weak and fragmented, whereas further north, the magnetic anomalies are more obvious. On the northeastern side of Lake Ankeleenjärvi this gneiss zone forks and one fork continues northeastwards to Lake Monninjärvi.

In the other parts of the exploration area the graphite gneisses do not form large continuous sequences, as those previously described. For example on the eastern side of Lake Virmasjärvi the graphite- and sulphide-rich gneisses appear within sulphide-free gneisses as narrow and fragmented bodies.

Limestones

About 700 metres to the east of Lake Tervalampi a zone begins running between the graphite- and suphide-rich gneisses northwest to Lake Luomanen and from there on to the northern end of Lake Ankeleenjärvi. Very long continuous negative gravity anomalies are associated with this zone. On the magnetic map the positive anomalies are missing from the same zone, whereas the weak negative anomalies are abundant. Since the negative anomalies cannot be interpreted as caused by the dip of stronger magnetic formations situated on both sides of the zone, the zone represents a rock type, which is very weakly magnetic and which has a lower density than the surrounding rocks. On these grounds the zone as a whole has been interpreted as limestone. Not one exposure has been found in the whole 10 km long zone. However, at the NW end of the zone on the northern side of Lake Ankeleenjärvi there is a small limestone quarry in production. However, later when some electromagnetic indications on the edge of this zone were drilled, limestone was encountered which proved that the interpretation of this area was correct. The drilling was carried out in the SE part of the limestone zone. The whole zone has not been pierced here either. Especially in the southeastern part of the limestone zone weak electric conductors are encountered. These are caused chiefly by the sulphide- and graphite-rich gneiss xenoliths, as was established also by diamond drilling. The connection between the geophysical anomalies and the limestone met with in association with the Hällinmäki deposit has been described earlier. Limestone together with amphibolites has been observed elsewhere in diamond drilling, but it usually appears as such narrow belts, that it has no influence on the general anomaly pattern.

Peridotites and gabbros

The peridotites and gabbros have a very small share in the Virtasalmi area. No larger massifs have been encountered, but peridotites and gabbros appear as small bodies together with diorites. They are extremely poor in magnetite, which is obvious from the susceptibility determinations reported earlier. Thus they are not connected to the magnetic anomalies, but are situated outside them. Because of their high density they are comparatively easy to locate from the gravity map, provided the dimensions of the bodies are sufficiently large. On the basis of outcrops a peridotite and gabbro occurence has been established on the southeastern side of Lake Virmasjärvi at Hulkkonen. It is also clearly recognisable as a positive anomaly on the gravity map. There are several roundish positive gravity anomalies on the eastern and northeastern side of Lake Ankeleenjärvi, in which the shape of the contours often approaches that of a circle. The usual interpretation is that they are caused by basic plutonic rocks. Exposures have only been found on a few of such gravity anomalies, in which case it was ascertained that the gravity anomalies were produced by peridotite or gabbro.

Diorites

The diorite group includes a differentiation series in which the composition of the rocks varies from diorite to trondhjemite. Diorites and quartz diorites are the most general types as deduced from the outcrop observations. As the mineral composition varies, so do also the physical properties with regard to density and magnetism. In addition, abundant amphibolite or gneiss xenoliths are associated here and there with diorites. Table 26 lists the modal composition of typical plutonic rocks at Hällinmäki determined by L. Hyvärinen by means of an integration stage. From these compositions the author has calculated the densities for the rocks by employing the densities given in the footnotes of Table 26 for the minerals. It appears from Table 26 that the density of a rock type depends largely on the amount of femic minerals. Due to the rather large variation in density of the dioritic rocks they do not correlate especially well to the gravity anomalies. The presence of gravity anomalies in the diorite area greatly depends on the rocks bordering on it and whether diorite, quartz diorite or trondhjemite are in question. When diorites are in contact with amphibolites the diorite always occurs in an area of lower gravity than the surroundings, whereas with regard to gneisses the actual diorites form positive gravity anomalies. The distinguishing of quartz diorites and trondhjemites from sulphide-free gneisses is most difficult due to their similar density.

On the magnetic map the diorites usually remain in areas where the anomalies are under 1 000γ. However, in the extensive diorite massif on the western shore of Lake Virmasjärvi anomalies of over 1 000γ are encountered. These are caused by the amphibolite xenoliths embedded in the diorites and by the small amphibolite lenses, which are abundant in places. The diorites do not contain electric conductors.

TABLE 26

Mineral compositions of the dioritic rocks of the Hällimäki area according to L. Hyvärinen and their densities calculated with the aid of the compositions.

Rock type Thin section No.	Quartz %	Plagio-clase %	Biotite %	Horn-blende %	Cumming-tonite %	Acces-sory minerals %	Total %	femic minerals %	Calculated density g/cm³
Diorite 11 913	—	70.2 1)	5.3	22.3	—	2.2	100.0	29.8	2.85
Diorite 11 934	—	69.0 2)	7.3	22.3	—	1.4	100.0	31.0	2.84
Diorite 12 825	—	82.1 3)	2.9	3.6	8.2	3.2	100.0	17.9	2.79
Quartz diorite 12 819	38.7	46.6 4)	4.1	8.6	—	2.0	100.0	14.7	2.75
Quartz diorite 12 827	15.1	53.3 5)	14.4	13.5	—	3.7	100.0	31.6	2.85
Trondhiemite 12 838	22.6	63.8 6)	12.3	0.6	—	0.7	100.0	13.6	2.71

1) An_{38} 2) An_{35} 3) An_{36-40} 4) An_{28} 5) An_{28} 5) An_{26-30} 6) An_{20}

The accessory minerals are: ore minerals, apatite and zircon

The following densities have been used for the minerals: Quartz 2.65 g/cm³,

Plagioclase $\frac{Ab(\%) \cdot 2.62 + An(\%) \cdot 2.76}{100}$

Biotite 3.00 g/cm³

Hornblende 3.23 g/cm³

Cummingtonite 3.11 g/cm³

Accessory minerals 4.50 g/cm³

From the southern end of Lake Virmasjärvi to the southwest there is the exceedingly strong negative gravity anomaly of Putkola (Fig. 20). The anomaly is round, about 1.5 km in diameter, the gravity values in the centre being about 1.5 mGal smaller than at the edges of the anomaly. In the south, the negative anomaly is bordered by a positive arc-shaped gravity anomaly 1.5—1.7 mGal in magnitude. Correspondingly in the northwest there are strong positive anomalies outside the negative anomalies. The positive anomalies are caused by the amphibolites of the Narila-Litmanen sequence discussed earlier. On the gravity map depicted in Fig. 20 those outcrops are marked from samples of which density determinations have been made. Also the measured density values are marked on the map. The rock types encountered in the outcrops of the negative gravity anomaly area all belong to the diorites. The measured density values vary from 2.66 to 2.83 g/cm³, the average being 2.75 g/cm³. According to Table 26 these rocks belong rather to the quartz diorites and trondhjemites on the basis of their density. The reason for the fact that the depicted anomaly is so clearly distinguishable from its surrounding is the great density difference with the surrounding amphibolites and the very large dimensions of the massif.

The gravity anomalies in the diorite area from Putkola to the northwest are no longer regular. At the northern and northwestern edge of the Putkola anomaly the gravity values increase with great regularity to the Hällinmäki—Karhuniemi line,

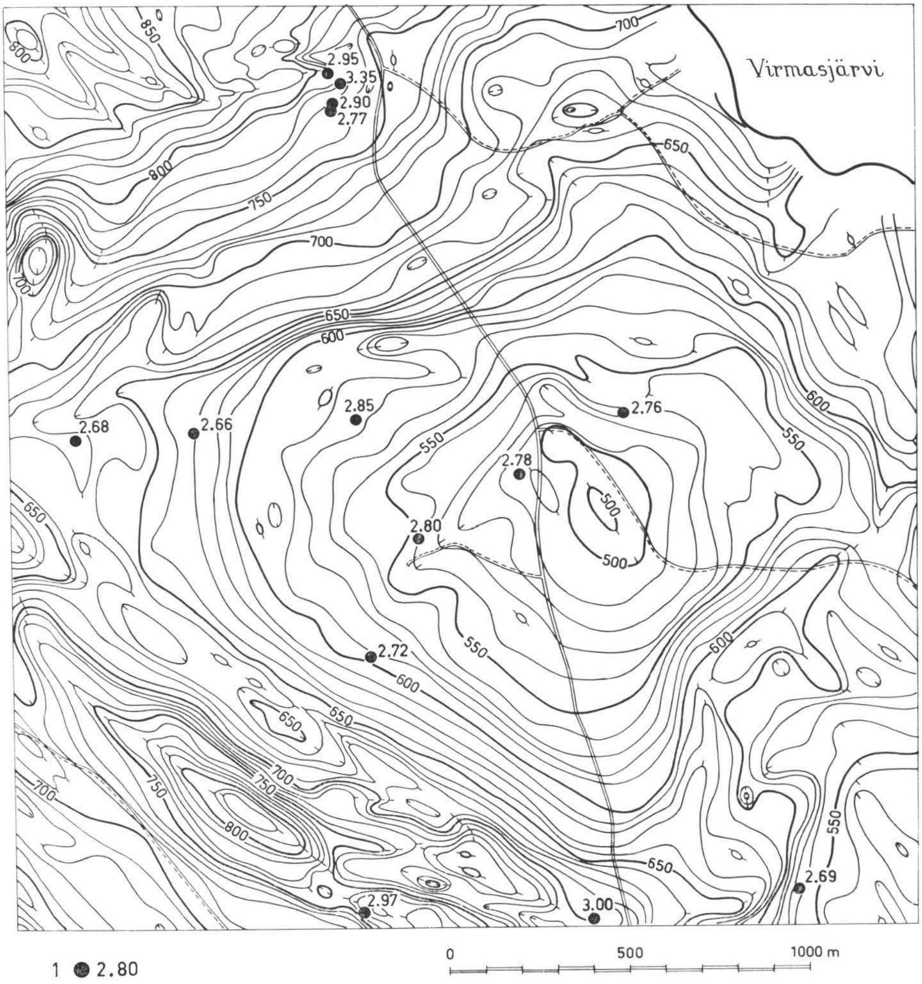

FIG. 24. The negative gravity anomaly at Putkola with surroundings. 1. Outcrop with measured density.

which is a zone of high gravity. There is a smallish gabbro body in this zone between the Hällinmäki and Karhuniemi amphibolites, whose influence is apparent on the gravity map in such a way that a part of the Hällinmäki anomaly contours turn northeastwards over the highway towards Karhuniemi.

Northwestwards from the Hällinmäki—Karhuniemi line the gravity values decrease again. Between Lake Virmasjärvi and the highway in the vicinity of Hällinmäki there is a fairly extensive but gently sloping positive gravity anomaly, which corresponds to the amphibolites encountered in the outcrops.

Geophysical anomalies and tectonics

The chief tectonic features of the supracrustal rocks are very much emphasised expecially on the magnetic and electromagnetic map. Arcs formed by gneisses containing pyrrhotite and graphite can be seen clearly both on the magnetic and electromagnetic maps. One arc runs SW from the southern side of Lake Ankeleenjärvi via the southwestern side of Lake Luomanen towards Narila and the second arc from the northern side of Lake Ankeleenjärvi via the northeastern side of Lake Luomanen towards Narila. Also the arc opening out towards the northwest between Lake Ankeleenjärvi and Lake Monninjärvi is obvious particularly on the magnetic map. Likewise on the electromagnetic map, especially on that showing the imaginary component of Slingram measurements, a gneiss zone round the eastern shore of Lake Virmasjärvi can be established as running fairly continuously from the eastern side of Narila. The course of the extensive amphibolite sequence on the western side of Lake Virmasjärvi from the eastern side of Lake Monninjärvi via the Litmanen pond to the northern side of Narila as well as its curving via the southern side of the Putkola diorite to the southern end of Lake Virmasjärvi is clearly visible on the magnetic and gravimetric maps. Its continuation under Lake Virmasjärvi and change of direction via Lake Valkeajärvi to the northwest can be observed only with the aid of the magnetic anomalies.

The influence of the dip of the large formations does not appear in the anomaly pattern given by the appended maps. However, on the more detailed electromagnetic Slingram maps the dip of the conducting zones can be determined with the aid of the asymmetry of the anomalies. Advantage has been taken of this when carrying out diamond drilling.

In connection with the deposit of Hällinmäki mention has been made earlier of the Turam indications, with which very sharp negative gravity anomalies were associated in places, and which, on the basis of drilling, were proved to have been produced by a fracture zone. Turam indications of corresponding type which follow the strike of the rocks, and which are due to fracture zones, are also encountered in the amphibolite area on the southeastern side of the Litmanen pond.

SUMMARY

The first part of the present study deals with the extent to which methods, used for gravity measurements and developed during the survey of rather limited areas, could be also applied without modification to the investigation of more extensive regions. It has been shown that the location and levelling of observation stations can be performed so accurately by means of the methods described that the reductions of the gravity observations do not induce errors greater than those existing in the

gravity observations. In connection with the correction calculations a method is introduced which permits the computation of the latitude correction in the rectangular Gauss-Krüger coordination.

The Virtasalmi area is composed of various sub-areas measured at different times and joined together by their sides. At the last stage of the gravity measurements a special control survey was made, the purpose of which was to estimate the magnitude of the errors involved in joining up the sub-areas. The control measurements showed that no drift of the gravity plane had taken place in the area. Further it demonstrated that the careful field work of an experienced crew permits the use of a simple sub-area method with sufficient accuracy in areas measuring 50—100 sq. km. However, it should be advantageous in areas exceeding 50 sq. km to establish a network of base stations, to which the various sub-areas could be tied. Thus the accuracy of the measurements could be controlled at various stages of the field work.

In connection with the control measurements, tying to the gravity stations of the Geodetic Institute was also carried out. This has permitted the computation of the correction needed to convert the gravity values of the Geological Survey into those of the absolute system of the Geodetic Institute. Also the value of the transition correction i.e. the difference between the relative Bouguer values of the Geological Survey and the Bouguer anomalies of the Geodetic Institute is given.

The second aim of this study has been to investigate the possibility of using gravity observations in addition to other geophysical measurements for the geological study of the Virtasalmi area. Gravity observations are essential for the location of ore bodies whose magnetic and electric properties do not differ from those of the country rock. Also, they are of great importance when it has to be decided whether the conducting zones located by means of the electromagnetic measurements are caused by compact sulphide ores or by schists containing graphite and sulphides.

In the part of the study which deals with the interpretation of the geophysical observations, the general geological features of the Virtasalmi area are presented together with the physical properties of the rocks involved. The possibilities of employing the physical properties of the rocks for interpretation are discussed. In the last section the manifestation of the variation in the rock types and the tectonic features as geophysical anomalies are described.

The study on the Virtasalmi area indicates that through geophysical measurements it is possible to obtain a considerable amount of new information concerning the general geology and rocks of the area under consideration. The continuation of most of the rocks encountered in the outcrops and their contacts has been verified by means of the geophysical anomalies. Also, many formations which do not outcrop, as e.g. the extensive limestone zone at Virtasalmi, and several ultrabasic bodies have been localised. Further, it is of great significance that on the basis of the geophysical investigations the intensive search for outcrops and excavation can be concentrated upon limited areas.

When the geophysical investigation directed to an area characterized by various rock types which differ from each other in their mode of formation and their physical properties it is urgent for the interpreter to have at his disposal results obtained from different methods. In the Virtasalmi area, for example, it would not have been possible to settle the nature of the extensive conducting zones without the gravity observations. Similarly the distinction of the limestone zone and the ultrabasic bodies from other non-magnetic rocks would have been impossible without gravimetric measurements. The gravity observations have also decisively contributed to the identification and localisation of the amphibolite occurrences.

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APPENDIX 1

CONTROL SEQUENCE I

Observation stations

Obs. time	653544	653545	653546	653547	642306	642305	642304	653587	653586	653585	653584	653583	653582	653581	653544					
12^h 20	7236.3			Δ g'	$\overline{\Delta g'}$	k	$\overline{\Delta g}$													
26	(7236.3)	7718.0		+481.7																
30	7236.3	(7718.5)		+482.2	+481.9	+0.3	+482.2													
33		7718.9																		
38		(7719.5)	8250.6		+531.1															
44		7719.9	(8251.0)		+531.1	+531.1	+0.3	+531.4												
49			8251.5																	
53			(8251.5)	8322.2		+70.7														
58			8251.5	(8322.2)		+70.7	+70.7	+0.3	+71.0											
13^h 02				8322.2																
08				(8323.0)	7965.0		-358.0													
15				8324.0	(7965.3)		-358.7	-358.4	+0.3	-358.1										
20					7966.0															
26					(7967.0)	7913.7		-53.3												
31					7967.8	(7913.7)		-54.1	-53.7	+0.2	+53.5									
36						7913.7														
43						(7914.0)	7527.3		-386.7											
48						7914.6	(7528.3)		-386.3	-386.5	+0.3	-386.2								
53							7529.2													
59							(7529.9)	7297.4		-232.5										
14^h 08							7531.0	(7298.4)		-232.6	-232.6	+0.3	-232.3							
15								7299.2												
20								(7299.2)	7334.9		+35.7									
25								7299.2	(7335.4)		+36.2	+36.0	+0.2	+36.2						
30									7335.8											
35									(7335.8)	7552.2		+216.4								
41									7335.8	(7552.2)		+216.4	+216.4	+0.3	+216.7					
46										7552.2										
51										(7552.2)	7618.5		+66.3							
57										7552.2	(7619.1)		+66.9	+66.6	+0.2	+66.8				
15^h 03											7619.5									
09											(7619.9)	7142.4		-477.5						
15											7620.4	(7143.3)		-477.1	-477.3	+0.3	-477.0			
21												7144.2								
27												(7144.2)	7417.3		+273.1					
33												7144.2	(7417.8)		+273.6	+273.4	+0.3	+273.7		
38													7418.2							
44													(7418.7)	7841.4		+422.7				
49													7419.1	(7841.8)		+422.7	+422.7	+0.3	+423.0	
56														7842.3						
16^h 01														(7842.7)	7248.3		-594.0			
08														7843.3	(7249.3)		-594.0	-594.0	+0.3	-593.9
14															7250.2			ω =-3.9		

7718.0 Observed gravity, 10^{-2} mGal

(7718.5) Observed gravity reduced to the observation time of an adjacent station

Δ g' Observed gravity difference

$\overline{\Delta g'}$ Observed average gravity difference

ω Closure error

k Correction due to closure error

$\overline{\Delta g}$ Smoothed gravity difference

APPENDIX 2

CONTROL SEQUENSE II

Observation stations

Obs. time	653544	653543	653542	653541	653540	653639	A	B	C	653581					
8^h 56	7511.5			Δg'	$\overline{\Delta g'}$	k	$\overline{\Delta g}$								
9^h 01	(7514.3)	7246.8		-267.5											
06	7517.1	(7250.4)		-266.7	-267.1	+1.1	-266.0								
10		7253.4													
16		(7253.8)	7945.0		+691.2										
22		7254.3	(7946.0)		+691.7	+691.5	+1.1	+692.6							
27			7946.8												
33			(7948.7)	7708.4		-240.3									
39			7950.6	(7710.7)		-239.9	-240.1	+1.1	-239.0						
45				7713.1											
50				(7714.1)	7100.2		-613.9								
54				7714.9	(7101.4)		-613.5	-613.7	+1.1	-612.6					
59					7103.0										
10^h 05					(7104.0)	6823.5		-280.5							
10					7104.8	(6825.2)		-279.6	-280.0	+1.1	-278.9				
16						6827.2									
22						(6828.7)	7100.6		+271.9						
31						6830.9	(7101.7)		+269.8	+270.9	+1.1	+272.5			
37							7102.5								
44							(7103.0)	7101.0		-2.0					
50							7103.4	(7100.4)		-3.0	-2.5	+1.0	-1.5		
55								7100.0							
11^h 02								(7101.3)	7889.8		+788.5				
10								7102.8	(7893.4)		+790.6	+789.6	+1.1	+790.7	
16									7896.3						
23									(7895.8)	8130.6		+234.8			
30									7895.4	(8130.6)		+235.2	+235.0	+1.1	+236.1
35										8130.6			ω = -9.8		

7511.5 Observed gravity, 10^{-2} mGal

7514.3 Observed gravity reduced to the observation time of an adjacent station

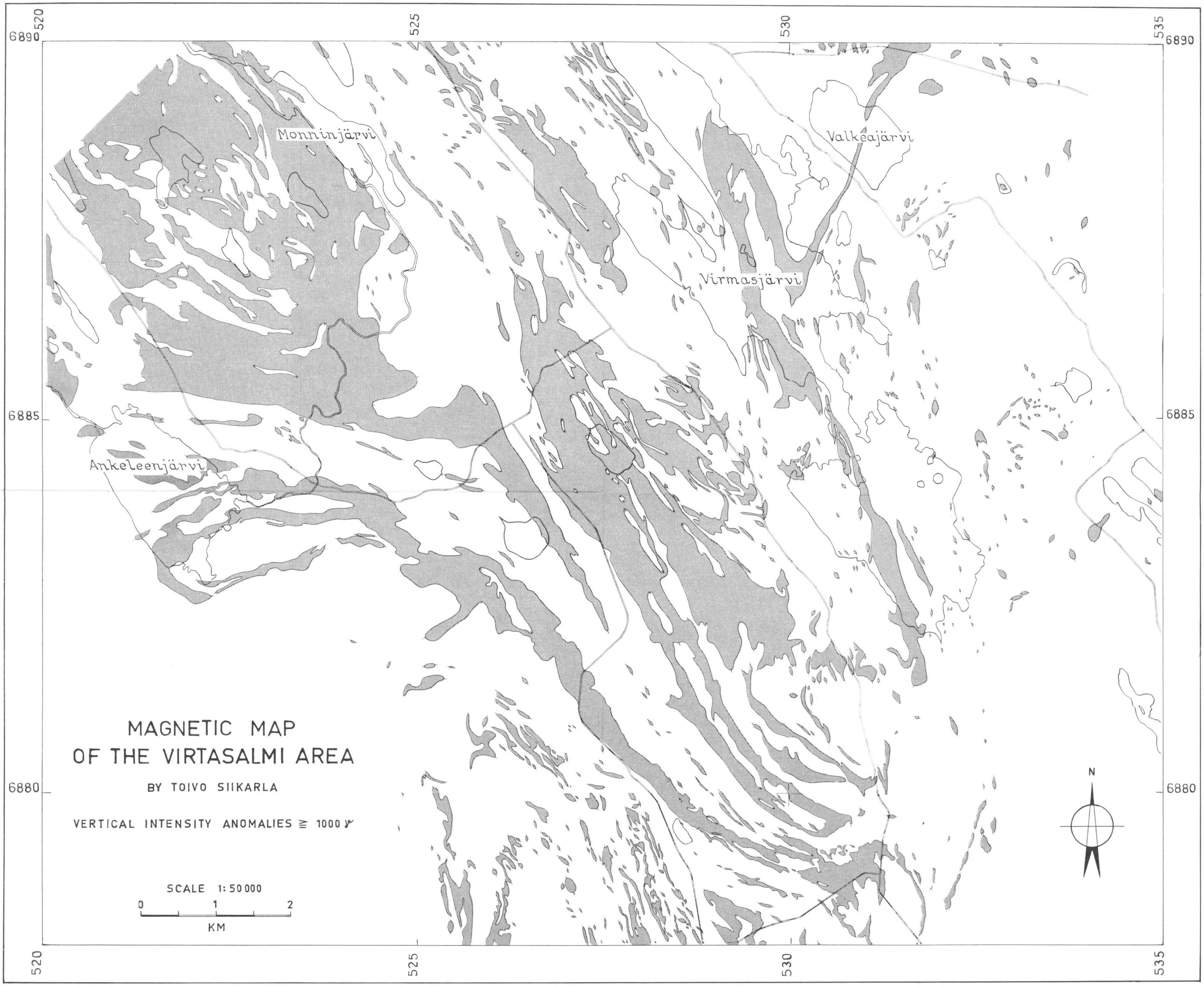
Δg' Observed gravity difference

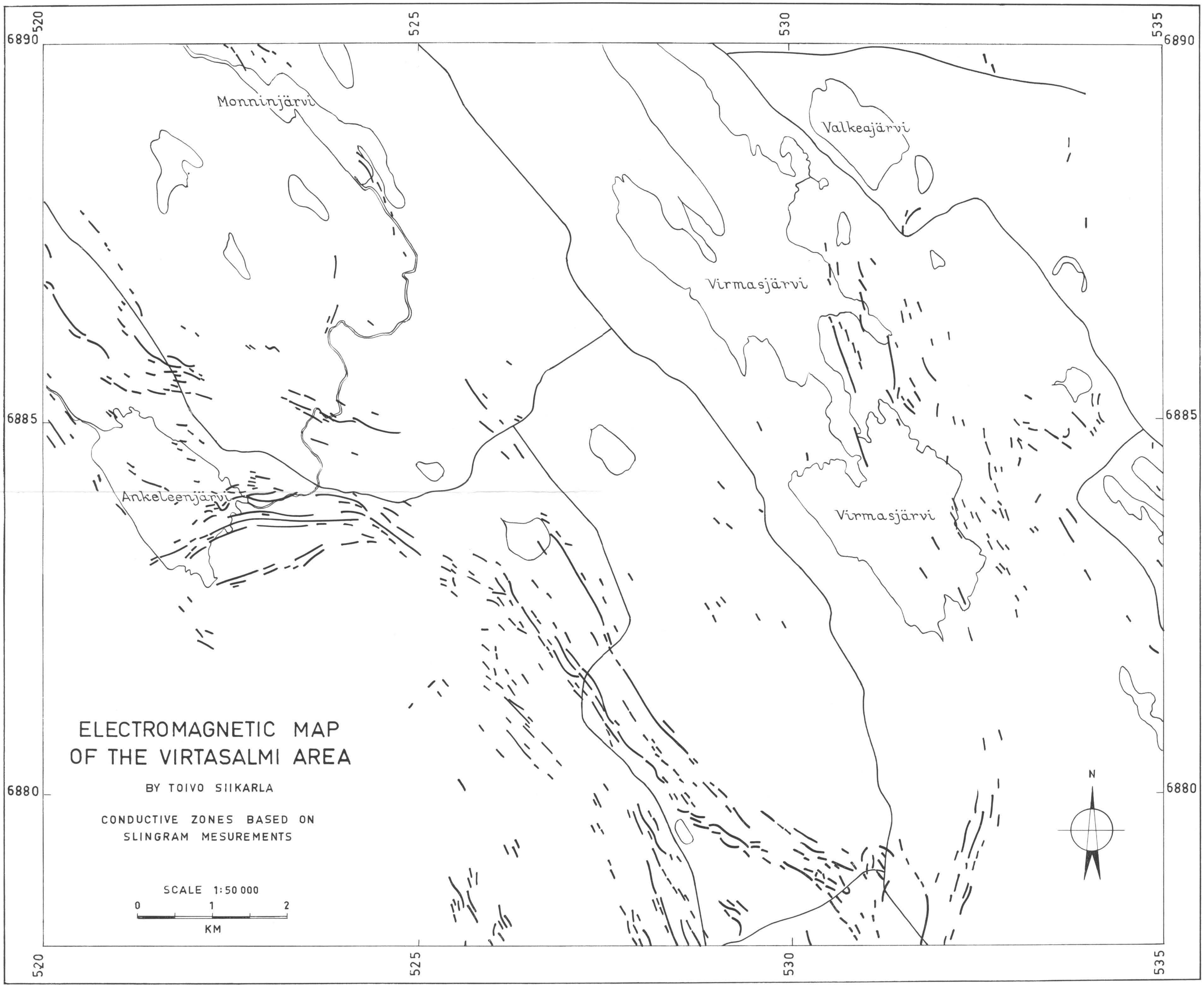
$\overline{\Delta g'}$ Observed average gravity difference

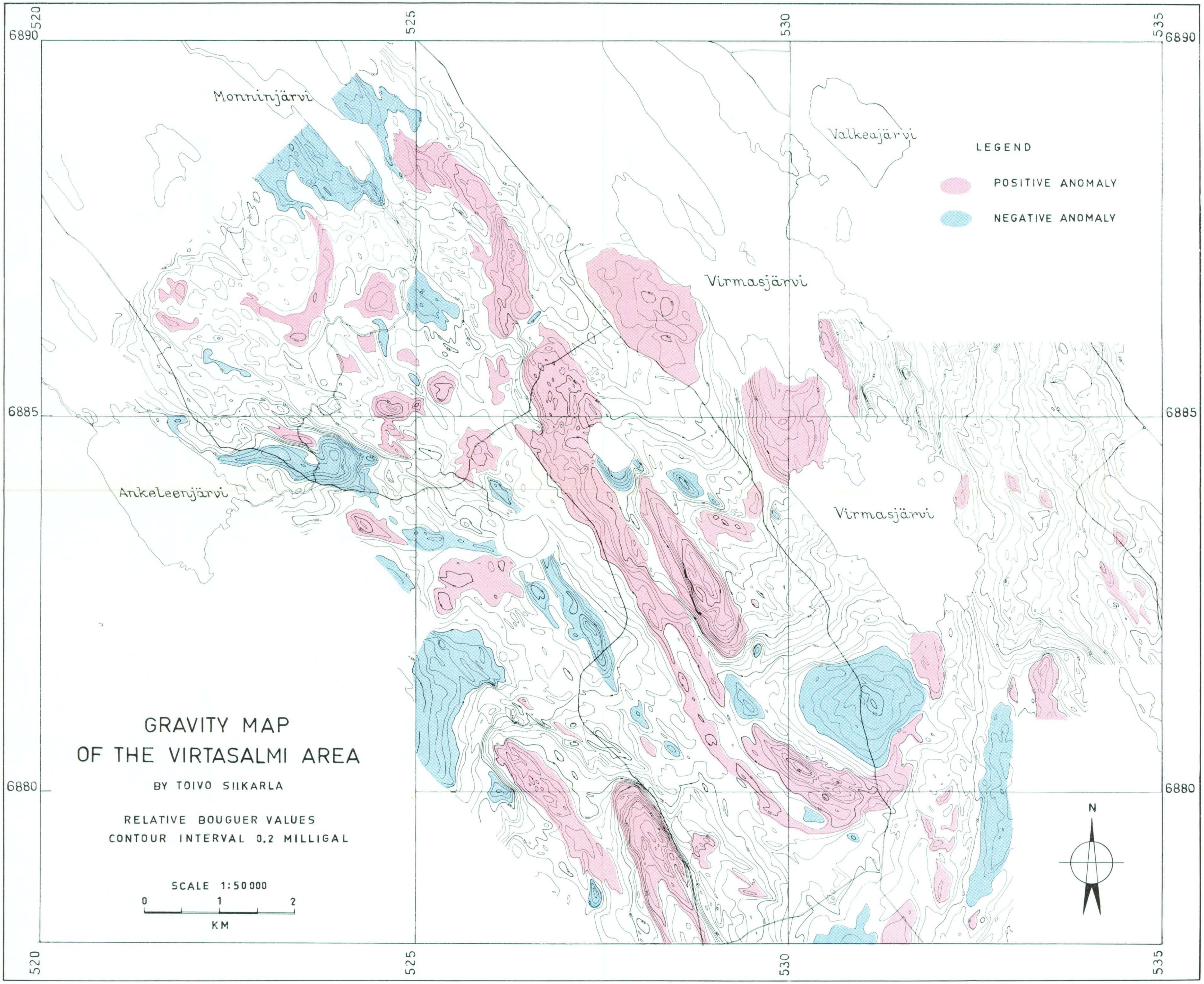
ω Closure error

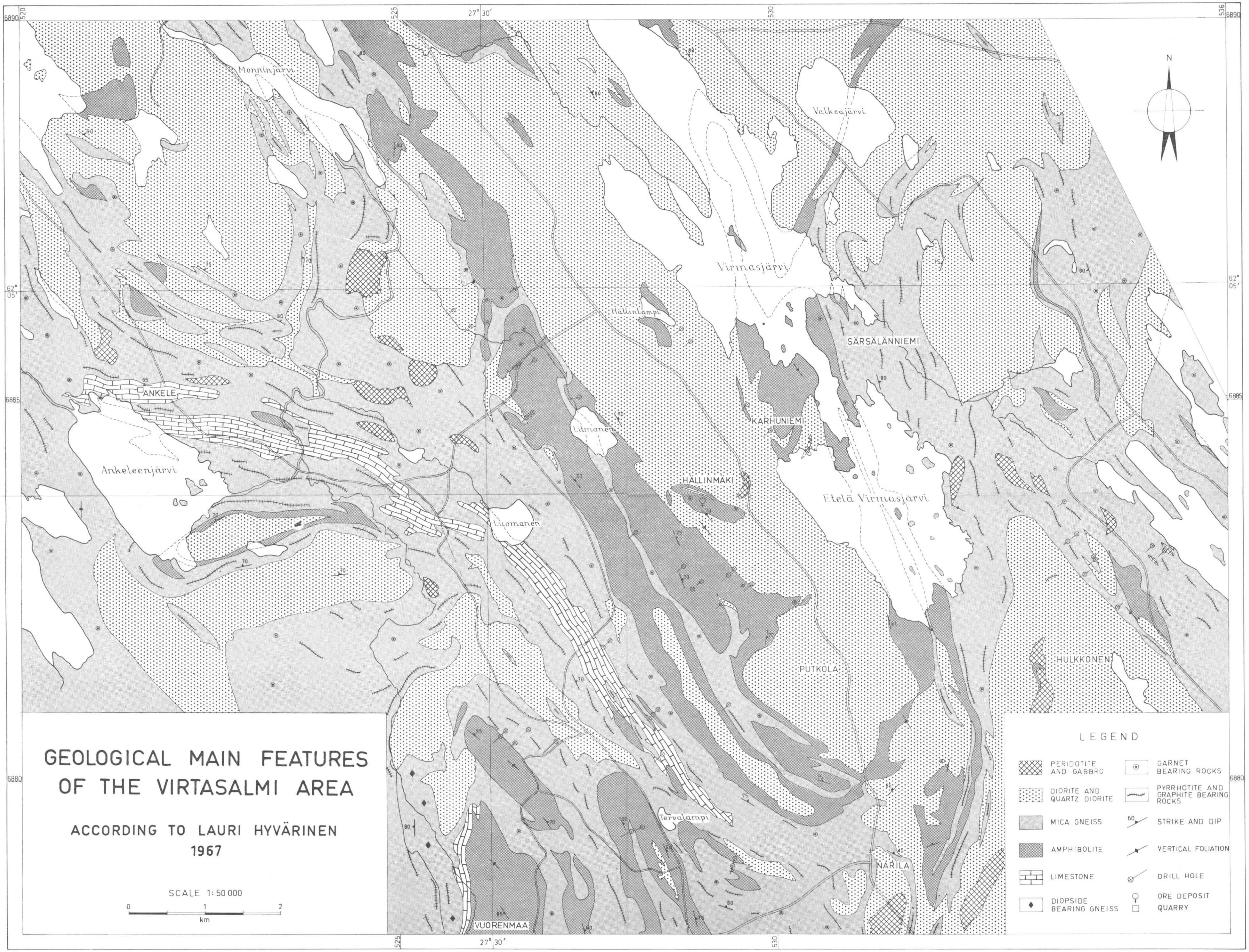
k Correction due to closure error

$\overline{\Delta g}$ Smoothed gravity difference


520
525
530
535
6890
6885
6880
Monninjärvi
Valkeajärvi
Virmasjärvi
Ankeleenjärvi
MAGNETIC MAP
OF THE VIRTASALMI AREA
BY TOIVO SIIKARLA
VERTICAL INTENSITY ANOMALIES ≧ 1000 γ
SCALE 1:50000
0 1 2
KM
N


520
525
530
535
6890
6890
6885
6885
6880
6880
Monninjärvi
Valkeajärvi
Virmasjärvi
Virmasjärvi
Ankeleenjärvi
ELECTROMAGNETIC MAP
OF THE VIRTASALMI AREA
BY TOIVO SIIKARLA
CONDUCTIVE ZONES BASED ON
SLINGRAM MESUREMENTS
SCALE 1:50 000
0 1 2
KM
N


GRAVITY MAP
OF THE VIRTASALMI AREA
BY TOIVO SIIKARLA
RELATIVE BOUGUER VALUES
CONTOUR INTERVAL 0.2 MILLIGAL
SCALE 1:50000
0
1
2
KM
LEGEND
POSITIVE ANOMALY
NEGATIVE ANOMALY
Monninjärvi
Valkeajärvi
Virmasjärvi
Ankeleenjärvi
Virmasjärvi
N
520
525
530
535
6890
6885
6880


GEOLOGICAL MAIN FEATURES OF THE VIRTASALMI AREA
ACCORDING TO LAURI HYVÄRINEN 1967
SCALE 1: 50 000
0 1 2
km
LEGEND
PERIDOTITE AND GABBRO
DIORITE AND QUARTZ DIORITE
MICA GNEISS
AMPHIBOLITE
LIMESTONE
DIOPSIDE BEARING GNEISS
GARNET BEARING ROCKS
PYRRHOTITE AND GRAPHITE BEARING ROCKS
STRIKE AND DIP
VERTICAL FOLIATION
DRILL HOLE
ORE DEPOSIT
QUARRY
N
Monninjärvi
Valkeajärvi
Virmasjärvi
Hällinlampi
SÄRSÄLÄNNIEMI
ANKELE
Ankeleenjärvi
Liimanen
KARHUNIEMI
HÄLLINMÄKI
Etelä Virmasjärvi
Luomanen
PUTKOLA
HULKKONEN
Tervalampi
NÄRILÄ
VUORENMAA
27° 30′
62° 05′
520
525
530
536
6890
6885
6880