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A STUDY OF THE GRAVITY ANOMALY ASSOCIATED WITH LAKE LAPPAJÄRVI, FINLAND

ABSTRACT

A circular negative gravity anomaly approximately -10 mgal in maximum value and 17 km in diameter is associated with Lake Lappajärvi. The related mass deficit is cirka $440 \cdot 10^{14}$g. A local positive residual anomaly of about 3 mgal occurs near the center of the negative anomaly. The available geological information and the interpretation of the gravity anomalies together suggest that Lake Lappajärvi is or resembles a complex hypervelocity impact crater. Besides the general structure, approximate dimensions of units defined by apparent mean density contrasts are derived.

INTRODUCTION

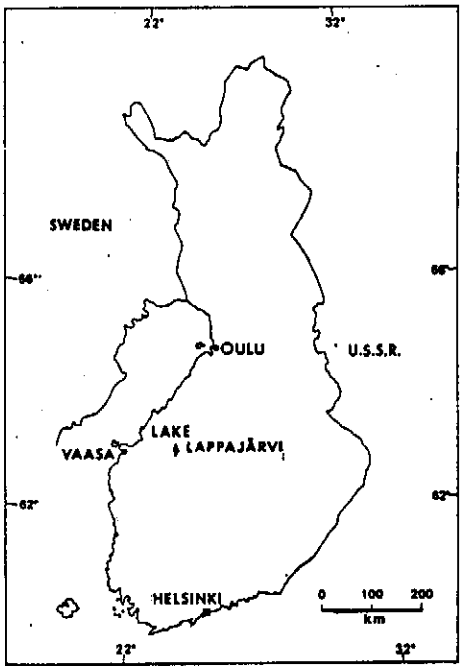

Fig. 1. Location map.

Figure 1. (After Lehtinen, 1976, p. 9)

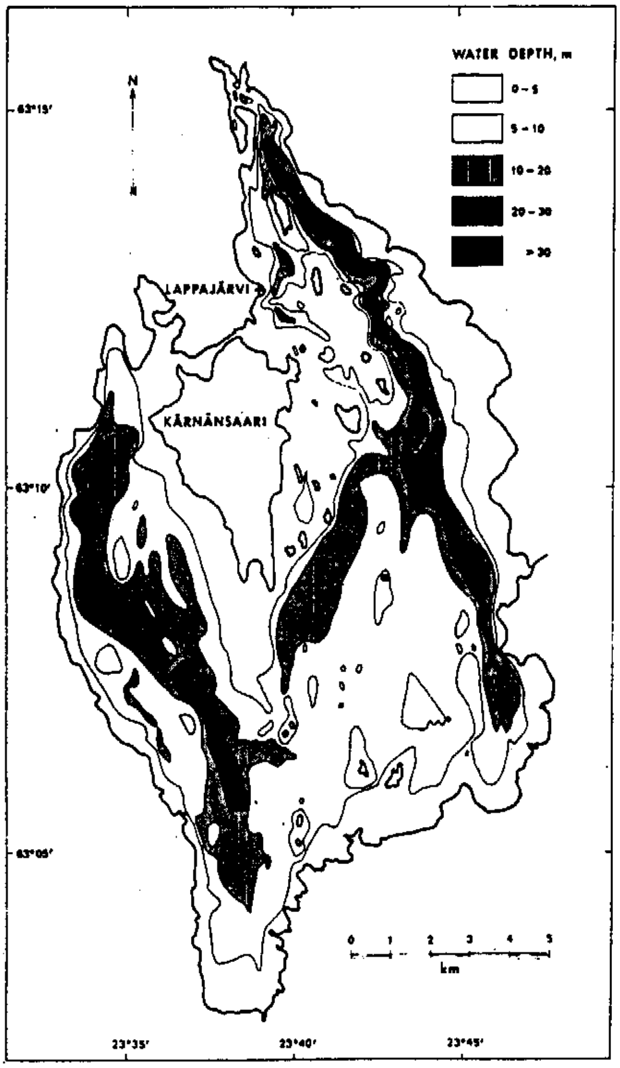

Fig. 2. Bathymetric chart of Lake Lappajärvi. Redrawn according to Odenwall (1934).

Figure 2. (After Lehtinen, 1976, p. 11)

Peculiar lava-like rocks, kärnäites, occur on the island Kärnänsaari in Lake Lappajärvi in western Finland. Originally they were described as volcanic rocks (e.g. Eskola, 1927). However, as in recent years worldwide accumulation of data resulted in a theory of terrestrial impact structures, new ideas about the origin of kärnäites were also put forth. Svensson and Lehtinen suggested that the kärnäites are impact lavas (Svensson, 1968; Lehtinen, 1970). Later on, Lehtinen reviewed available evidence, described in detail the petrology, the mineralogy and the shock metamorphic features of the Lappajärvi rocks and concluded that Lake Lappajärvi is a meteorite impact site (Lehtinen, 1976).

After Robertson and Grieve (1975) following four classes of impact structures are recognized as cited below:

" (1) small impact pits, up to 9 m in diameter. Associated meteorites are generally recovered intact and shock metamorphic effects are absent.

(2) impact craters, 9 to 90 m in diameter. Recovered meteorites are broken and deformed, but neither they nor the target rocks show shock effects.

(3) simple hypervelocity craters, 90 m to approximately 4 km in diameter, in the form of a basin with uplifted and overturned rim rocks.Fragments of meteorite are recovered from only the younger and smaller examples (cirka 10 per cent of this class). Both they and the target rocks have shock metamorphic effects.

(4) complex hypervelocity craters, generally larger than 4 km in diameter, with an uplifted central peak and a slumped or depressed rim. In the larger structures, a series of uplifts and depressions can occur concentric with the central peak, resulting in a multiring structure. The target rocks are shocked and the bolide as an entity is destroyed on impact.,"

Obviously, subsequent erosion and deformation have partly or totally annihilated many terrestrial impact craters, and the validity of criteria for identification of existing ones is still controversial. The suggested hypervelocity craters share common features, of which signs of shock metamorphism are considered to be most important. To avoid the question of origin, the epithet cryptoexplosion has been applied to structures produced by violent events involving intense shock.

Because shock metamorphism affects physical properties of rocks (e.g. density, magnetic susceptibility and remanence, resistivity and velocities of seismic waves) geophysical methods are useful in defining cryptoexplosion structures and their dimensions. Particularly, negative circular gravity anomalies are typical of them (Dence et al, 1968; Fudali and Cassidy, 1972; Innes, 1961; Milton et al, 1972; Stanfors, 1973; etc.). Gravity anomaly patterns may also contain irregularities due to melting of rocks and central uplift.

The purpose of this paper is to study the gravity anomaly associated with Lake Lappajärvi.

GRAVITY DATA

The Bouguer anomaly map (figure 3) is based on 260 gravity stations, which were measured with a Worden Standard Master gravimeter (SN 934). Most stations were established at bench marks for which levelled elevations were available. The remaining elevations were either levelled, or directly compared to the levelled surface of Lake Lappajärvi, or obtained through microbarometric measurements (14 elevations) with a mean error of about 0.5 m. The mean elevation of the gravity stations was 90 m and the range of elevations was 80 m.

Several stations were measured in the winter on the lake ice. Rods were lowered to the bottom of the lake through holes in the ice. The gravimeter was placed on a special mounting plate attached to the upper end of the rods. Supports on the surface were such that ice motions did not influence the rods. This technique secured accurate measurements but could be used only at shallow waters.

Gravity data were reduced by standard methods. The density value of 2.67 g/cm^3 was used to obtain Bouguer anomalies. Replacement of water by rock was included in the Bouguer reduction for the stations measured on the lake ice. Terrain corrections were not made. Appendix 1 contains the listing of the basic data.

The Bouguer anomaly map (Figure 3) was generated automatically by the General Purpose Contouring Program of California Computer Products, Inc. And the anomaly profiles in the following figures were interpolated using a simple weighting and smoothing method.

ROCK DENSITIES

Geologist Pipping kindly supplied rock specimens from Lappajärvi area for density determinations. Data in Table 1 is applied in this study.

TABLE 1. WET BULK DENSITIES OF LAPPAJÄRVI ROCKS

Type	Mean	Standard deviation	Number of specimens
granite	2.63 g/cm^3	0.05 g/cm^3	20
granodiorite	2.70	0.06	19
gneiss	2.71	0.07	28
mica schist	2.72	0.07	90
amphibolite	2.94	0.11	17

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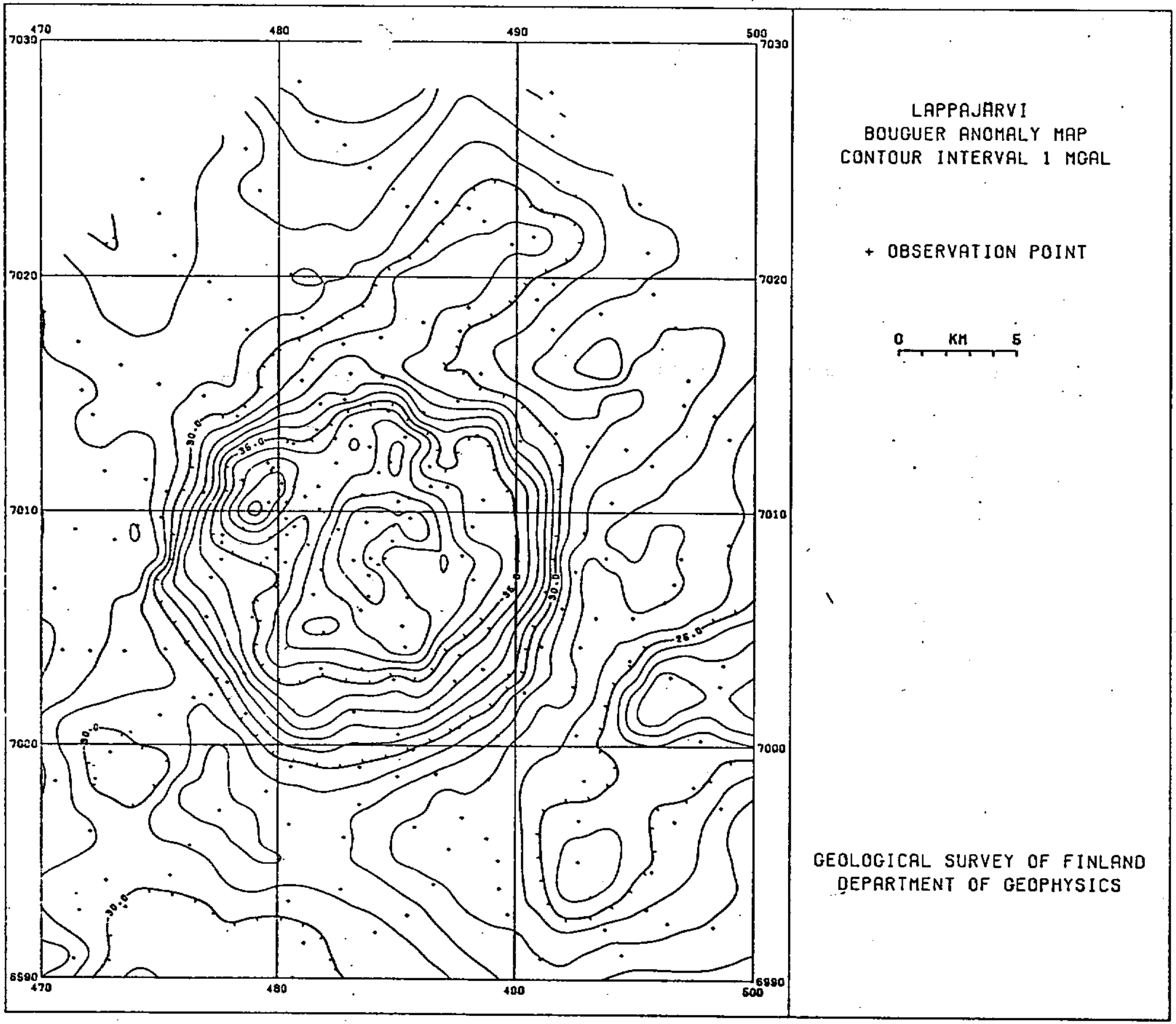


Figure 3. Lappajärvi Bouguer anomaly map.

TABLE 1. WET BULK DENSITIES OF LAPPAJÄRVI ROCKS (continues)

Type	Mean	Standard deviation	Number of specimens
kärnäite	2.54 g/cm^3	0.04 g/cm^3	13
shocked bedrock [1]	2.38	0.16 g/cm^3	11
impact breccia and suevite [1]	2.22	0.22 g/cm^3	10

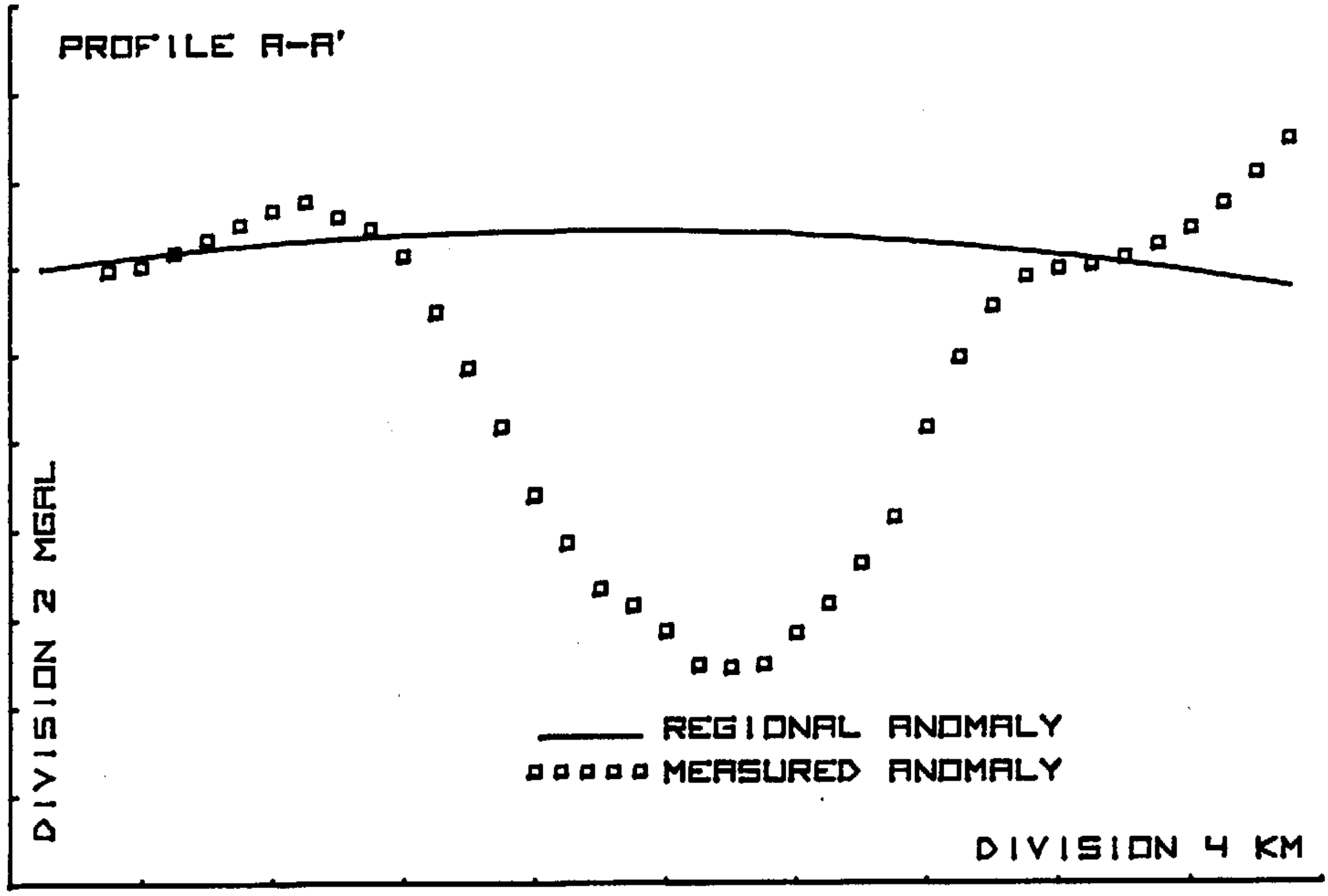
[1] cobbles from glacial gravels, identification by Pipping

The mean density of the country rock is estimated to be approximately 2.70 g/cm^3. Although the specimens of shocked bedrock, impact breccia and suevite are from glacial gravels, they indicate the presence of heterogenous low density rocks in the Lappajärvi basin.

THE CIRCULAR NEGATIVE BOUGUER ANOMALY

The most striking feature of the gravity map is the circular negative anomaly. It is caused by kärnäites, breccias and sediments in the Lappajärvi basin and by shocked and fractured bedrock. The gravity high in the south-eastern part of the map is probably caused by mafic rocks.

The regional gravity field was approximated by a second degree polynomial surface. Besides the data in Appendix 1, observations of the Finnish Geodetic Institute were used in deriving this surface. Figure 4 displays the measured and regional anomalies along the profiles A-A' and C-C' shown in Figure 5.



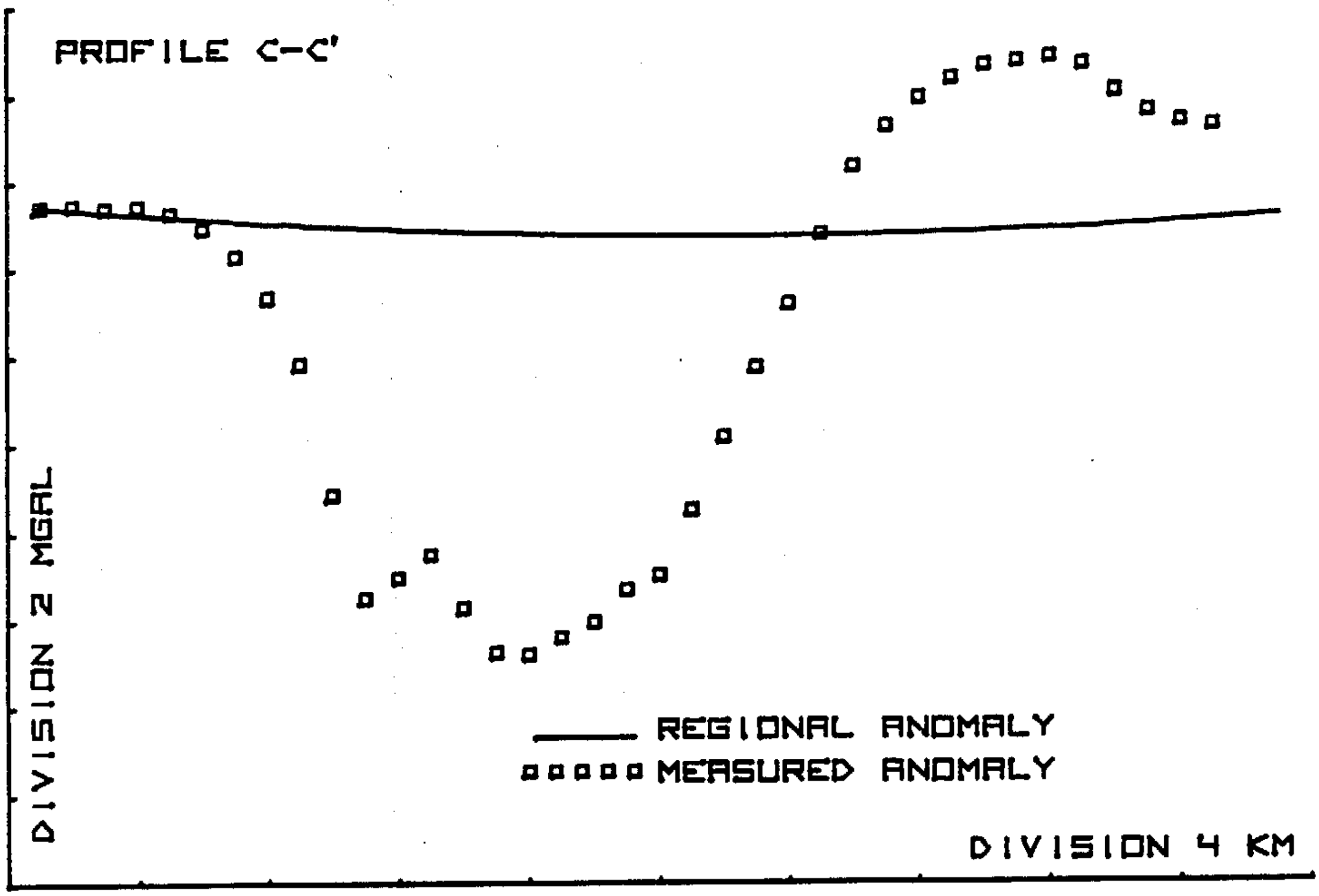


Figure 4. The regional-residual separation of the negative anomaly.

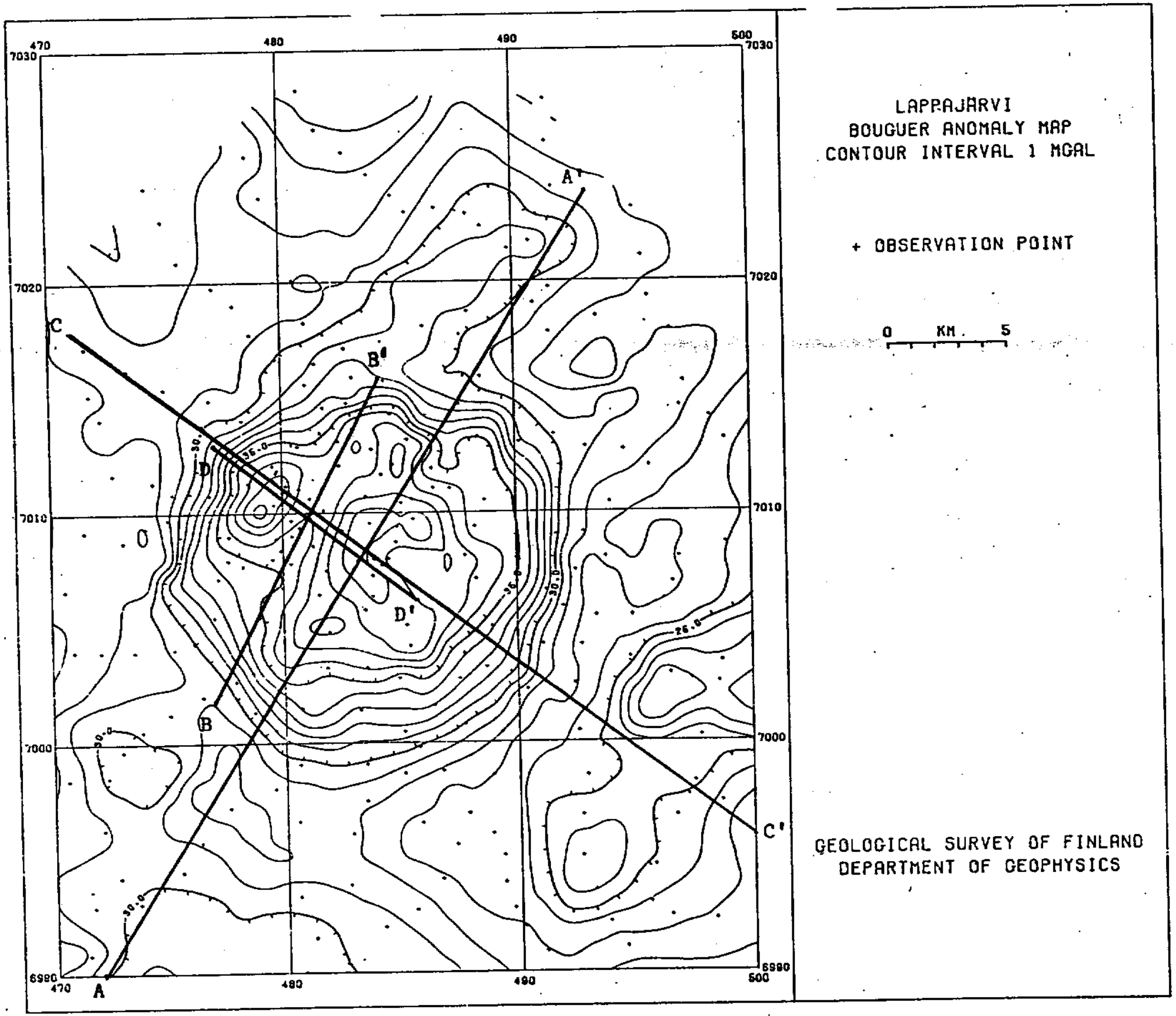


Figure 5. The locations of the profiles A-A', B-B', C-C' and D-D'.

In calculating anomalous masses the field outside the area of numerical integration is usually calculated by assuming that the entire mass is concentrated at its center. Consequently, the calculated value is dependent on the depth of the center of mass and cannot be unambiguously solved. Moreover, the calculated value contains errors made in the regional-residual separation and also the relatively small errors of numerical integration. The mass deficit given in Table 2 was calculated assuming that the center of the anomalous mass lies at depth of 0.5 km. The area of numerical integration was 10 times 10 km^2. The depth of 1.0 km would give a greater value by about 5 per cent, and the depth of 0.3 km would give a lower value by about 2 per cent.

TABLE 2. SOME CHARACTERISTICS OF THE CIRCULAR ANOMALY

MEAN DIAMETER	17 KM
MAXIMUM ANOMALY	-10 MGAL
MASS DEFICIT	$440 \cdot 10^{14}$ G
$\Delta M/D^{2.5}$	$-0.37 \cdot 10^{14}$ $G/KM^{2.5}$

Estimates of approximate depths of structural units defined by their apparent mean density contrasts and rough outlines of their shapes can be obtained through three-dimensional, single density contrast interpretation models. Figures 6a, 6b, 6c and 6d display the cross-sections of four different models along the profiles A-A' and C-C' (Figure 5). The models correspond to density contrasts of -0.48 g/cm^3 (difference in densities of impact breccia & suevite and country rock), -0.32 g/cm^3 (difference in densities of shocked bedrock and country rock), -0.16 g/cm^3 (difference in densities of kärnäite and country rock) and -0.08 g/cm^3 (it seems reasonable to assume that the density of shocked bedrock gradually approaches the density of country rock as a function of depth).

Figure 6a. Three-dimensional interpretation model consistent with the negative residual anomaly.

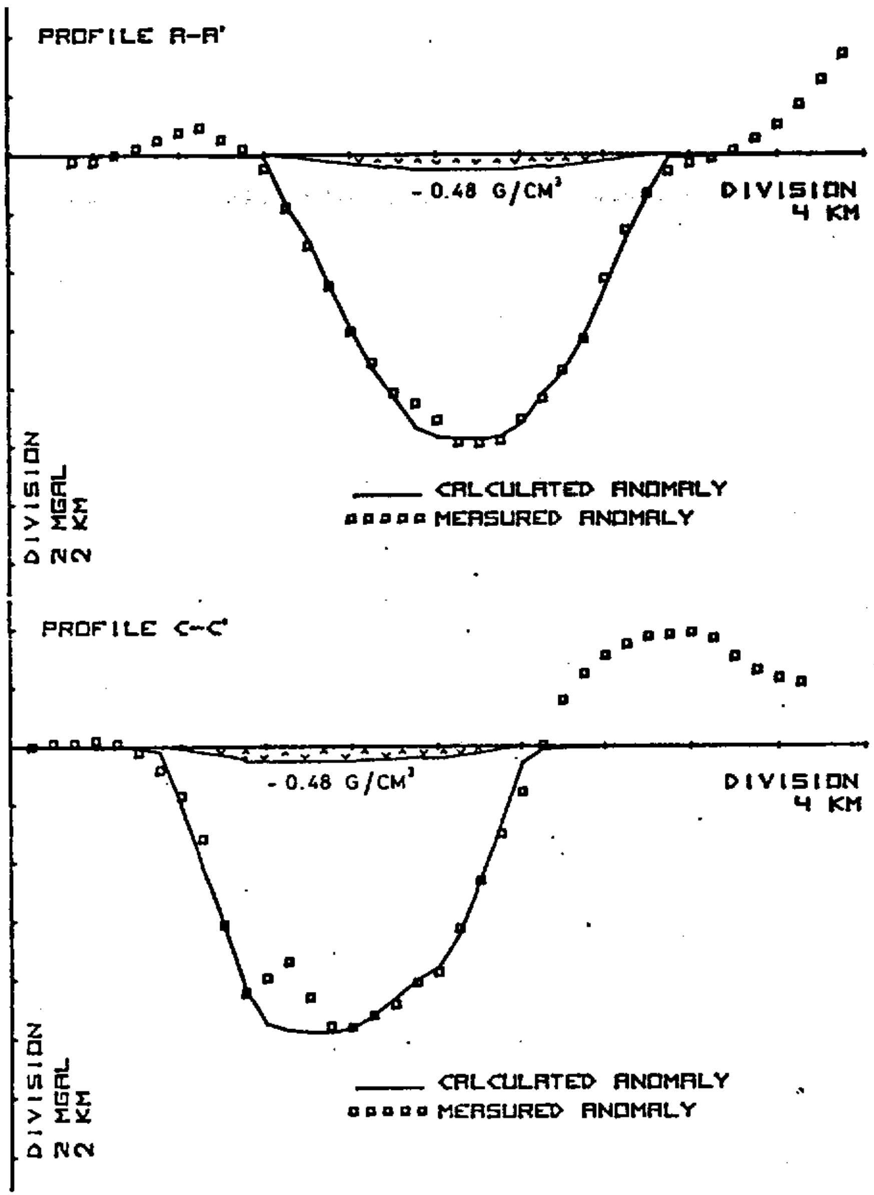


Figure 6b. Three-dimensional interpretation model consistent with the negative residual anonaly.

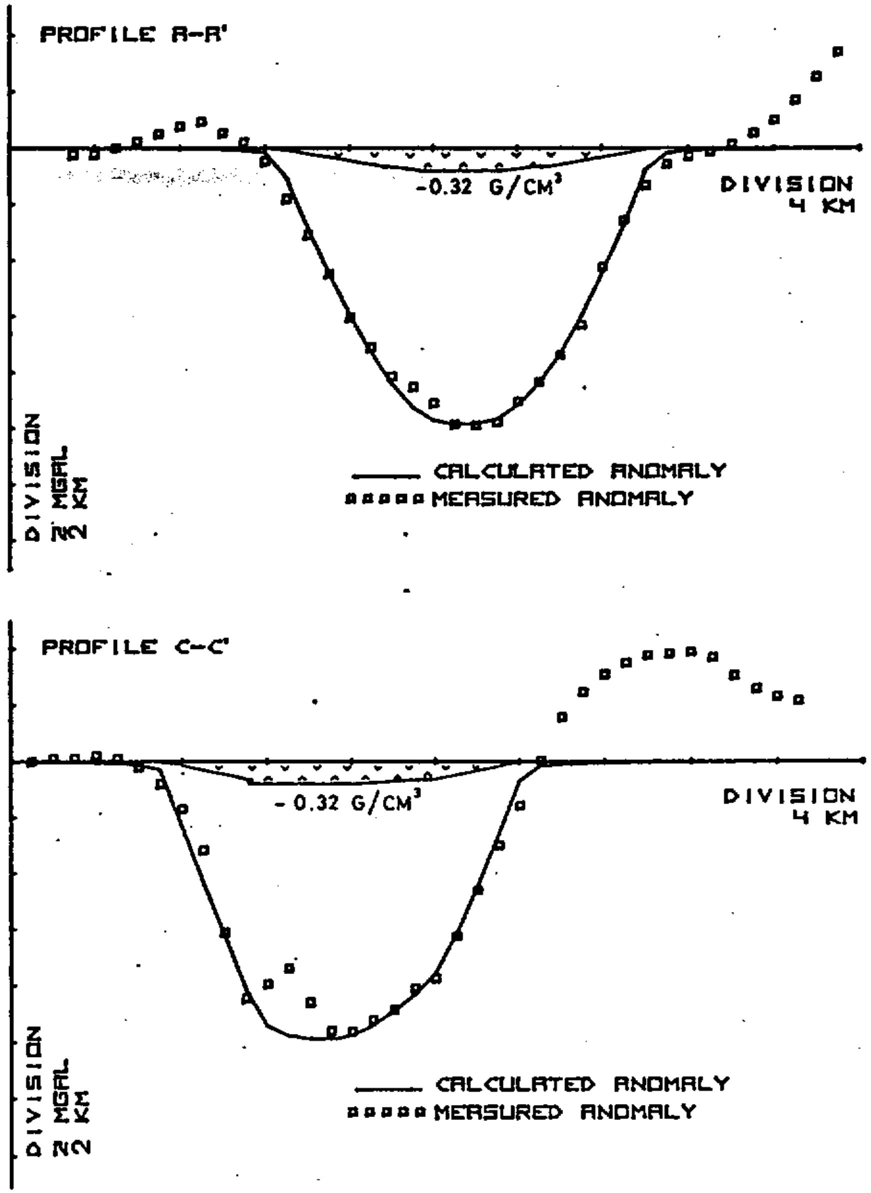


Figure 6c. Three-dimensional interpretation model consistent with the negative residual anomaly.

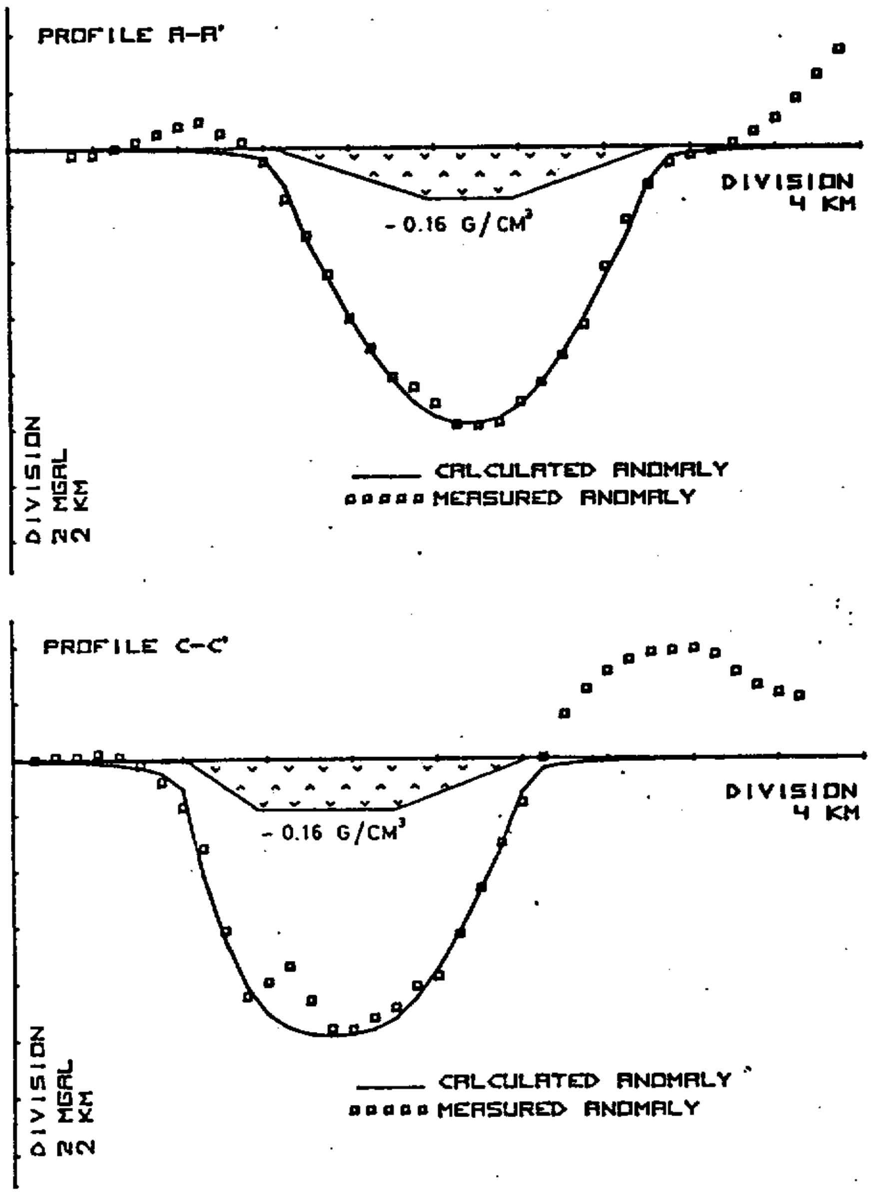
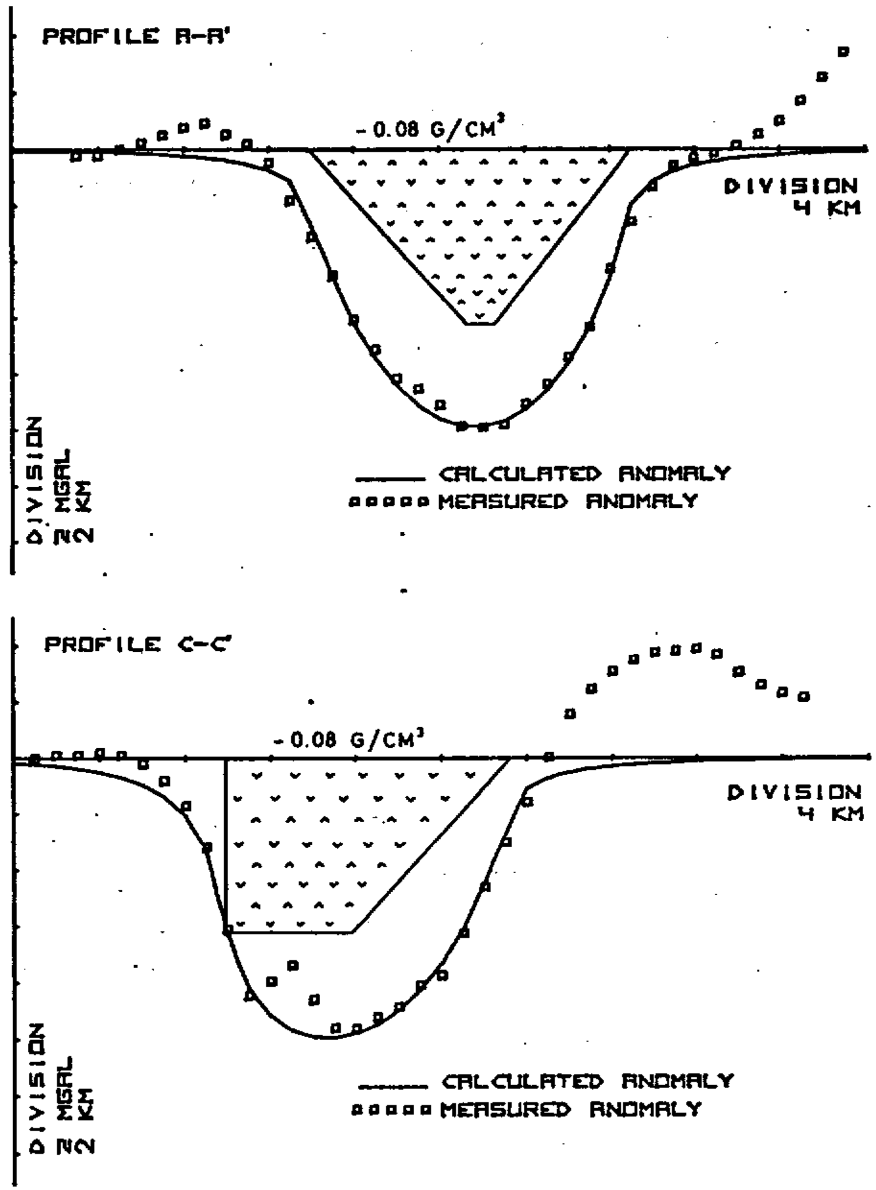


Figure 6d. Three-dimensional interpretation model consistent with the negative residual anomaly.



For example the approximate depth estimate for the unit defined by the apparent mean density contrast of -0.48 g/cm^3 is about 0.5 km.

THE CENTRAL POSITIVE RESIDUAL ANOMALY

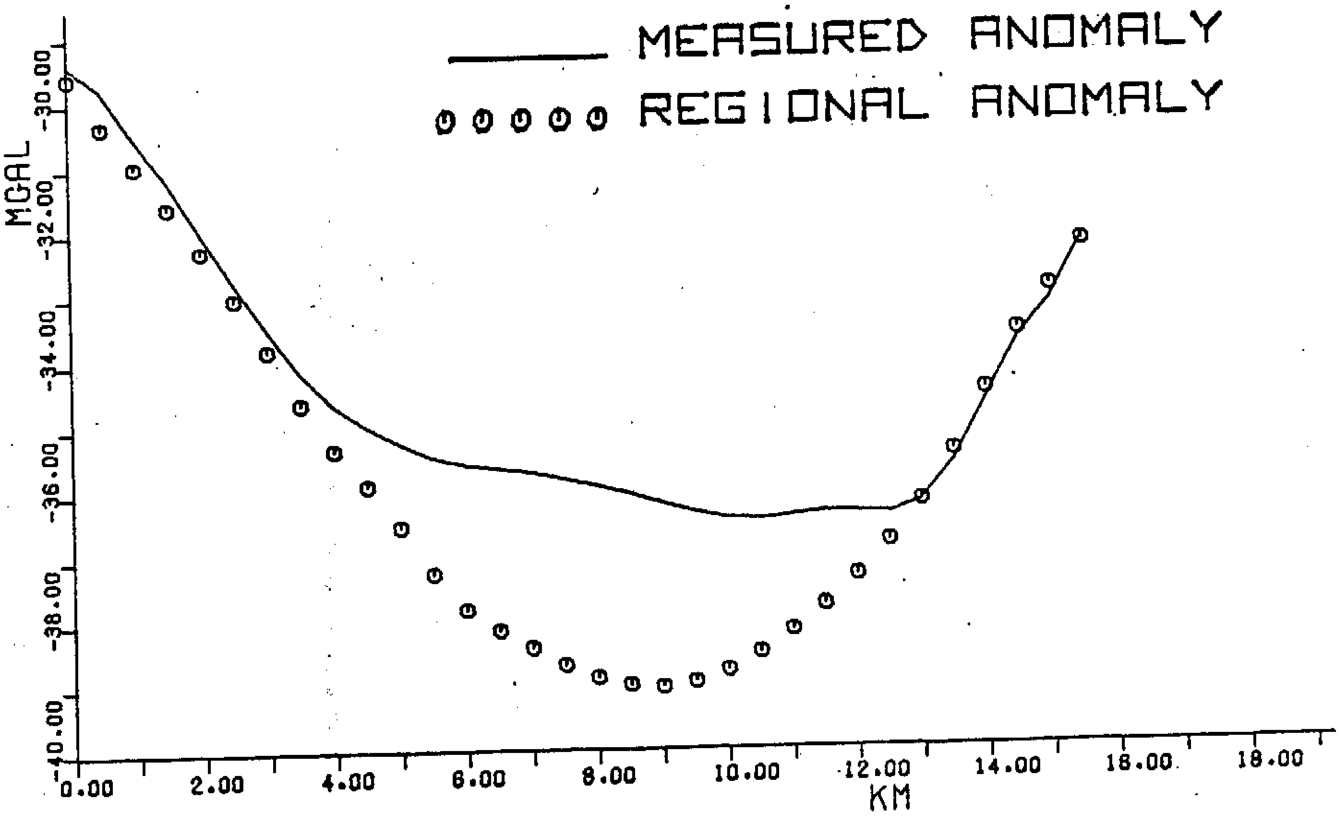
A local positive residual anomaly of about 3 mgal occurs near the center of the circular negative anomaly. The maximum residual coincides with some outcrops of kärnäite. The anomaly is caused by kärnäites, high density breccias and possibly shocked and fractured bedrock, which are surrounded by low density breccias and sediments. The anomaly suggests a central uplift and adjacent peripheral valleys filled by low density material.

The positive residual anomaly was obtained through a fourth degree polynomial approximation of the regional field. Figure 7 displays the measured and regional anomalies along the profiles B-B' and D-D' shown in Figure 5.

Estimates of approximate dimensions of units defined by their apparent mean density contrasts can again be derived by means of model interpretations.

Hypothesis 1: the residual anomaly is caused entirely by kärnäite. Two cross-sections of a model are shown in Figure 8. The contrast of +0.32 g/cm^3, which equals approximately the difference in densities of kärnäite and impact breccia & suevite, gives maximum thickness of about 0.25 km. +0.16 g/cm^3 would give a thickness of about 0.5 km. The result of the interpretation is outlined in Figure 10.

PROFILE B-B'



PROFILE D-D'

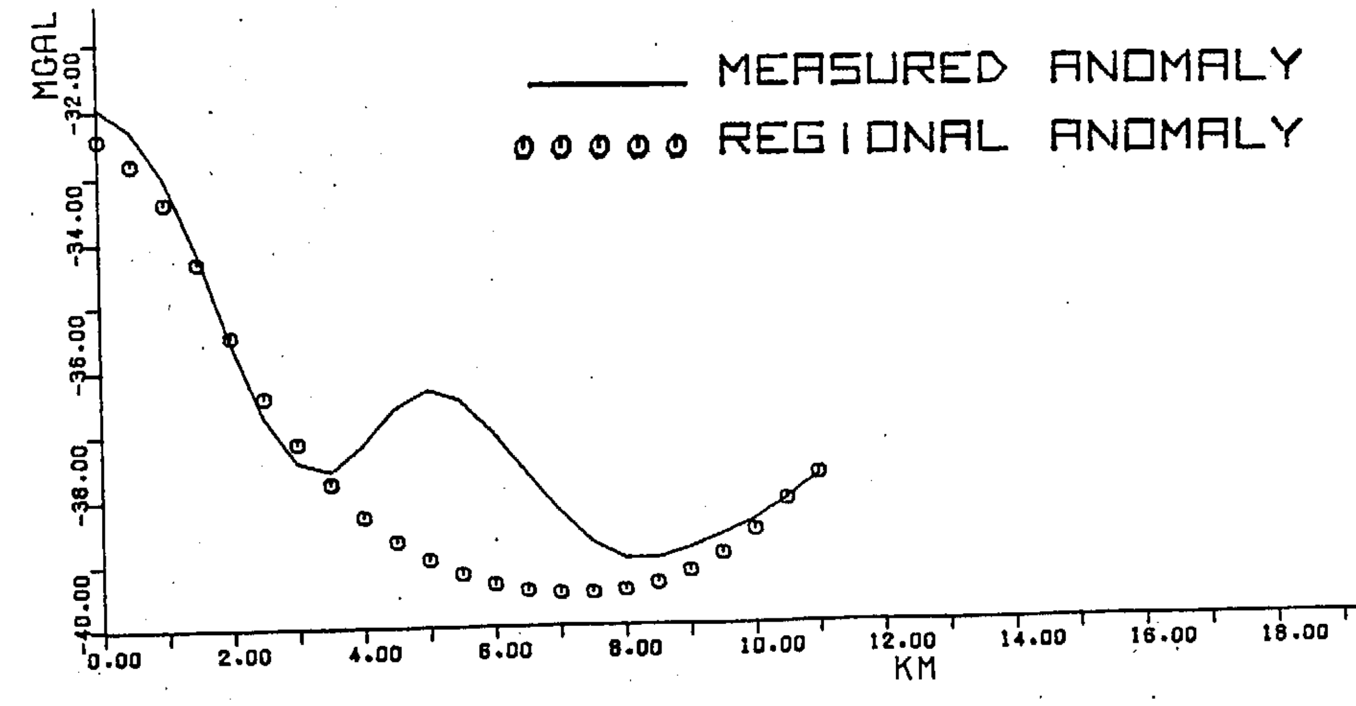


Figure 7. The regional-residual separation of the positive anomaly.

Figure 8. An interpretation of the positive residual anomaly.

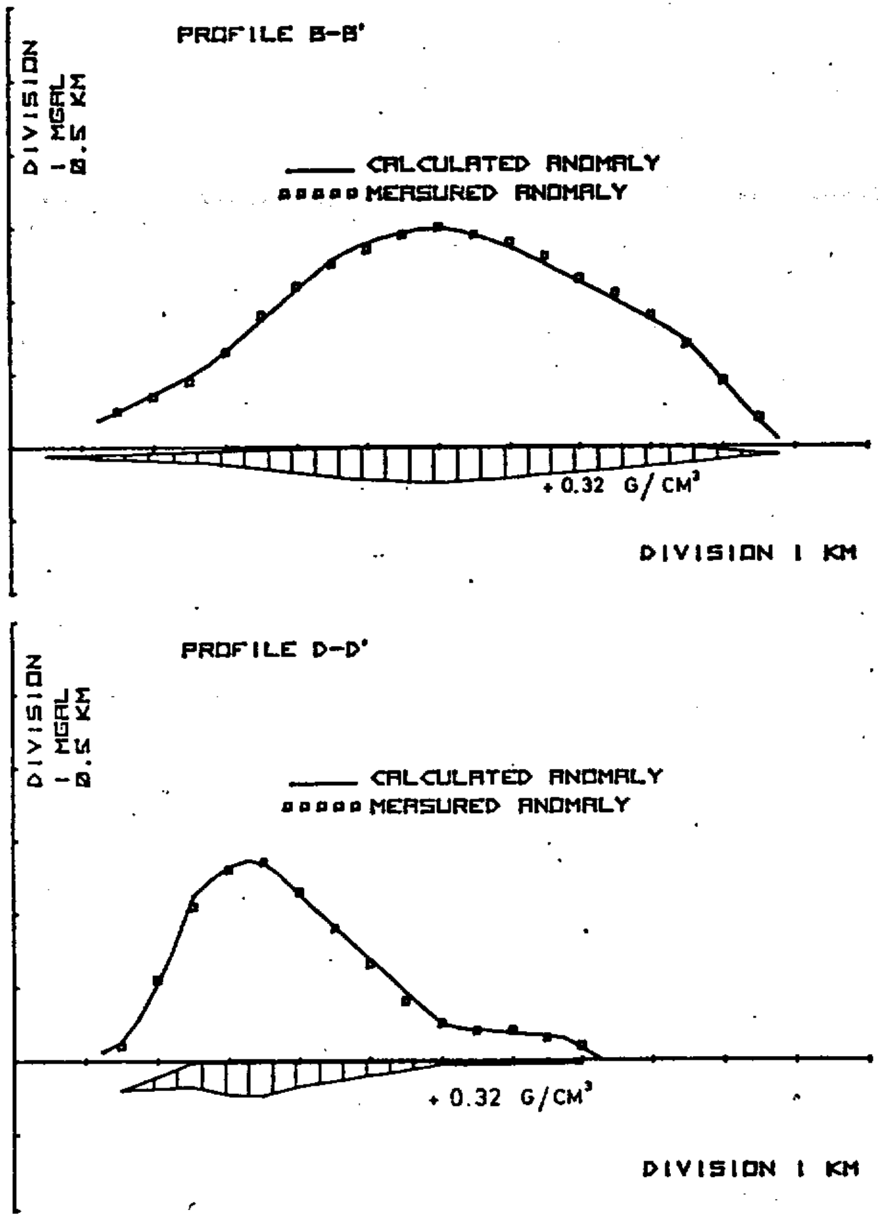
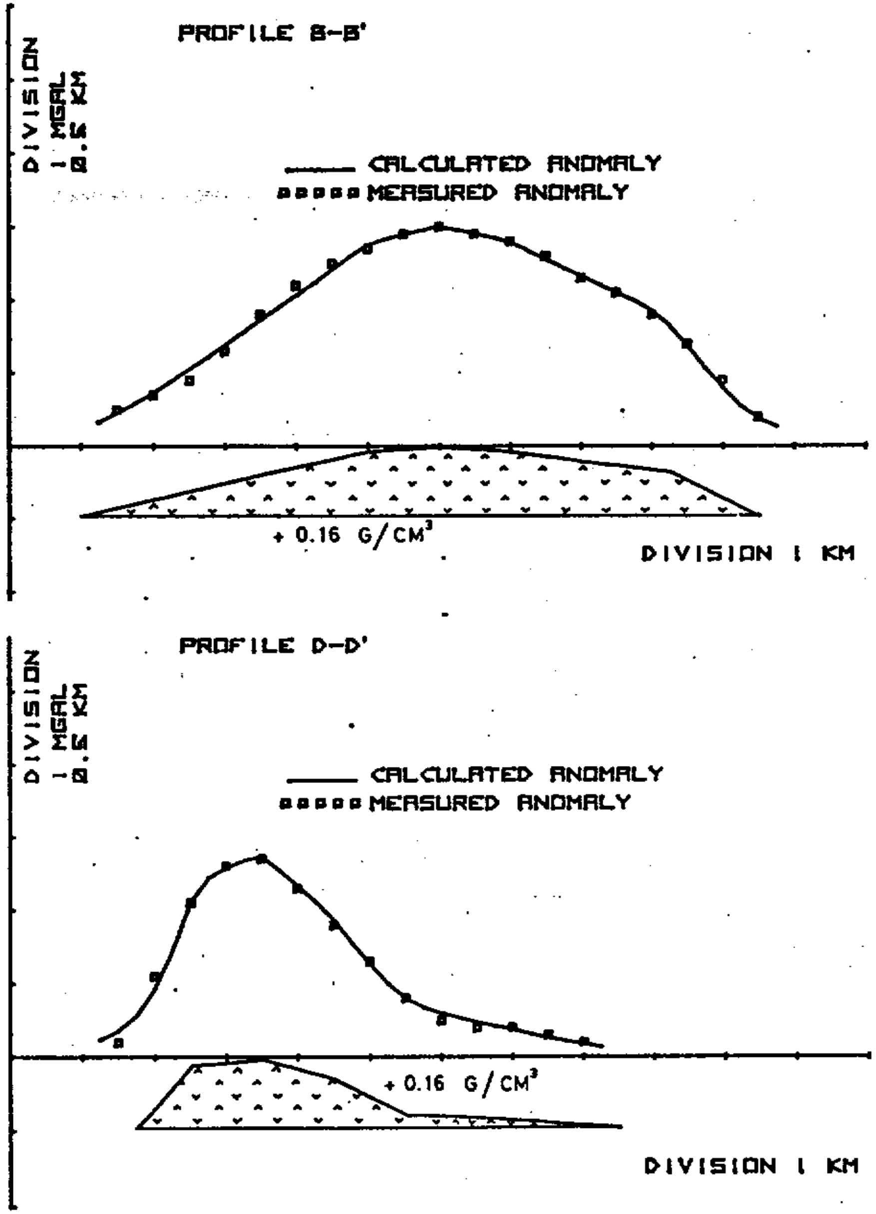


Figure 9. An interpretation of the positive residual anomaly.



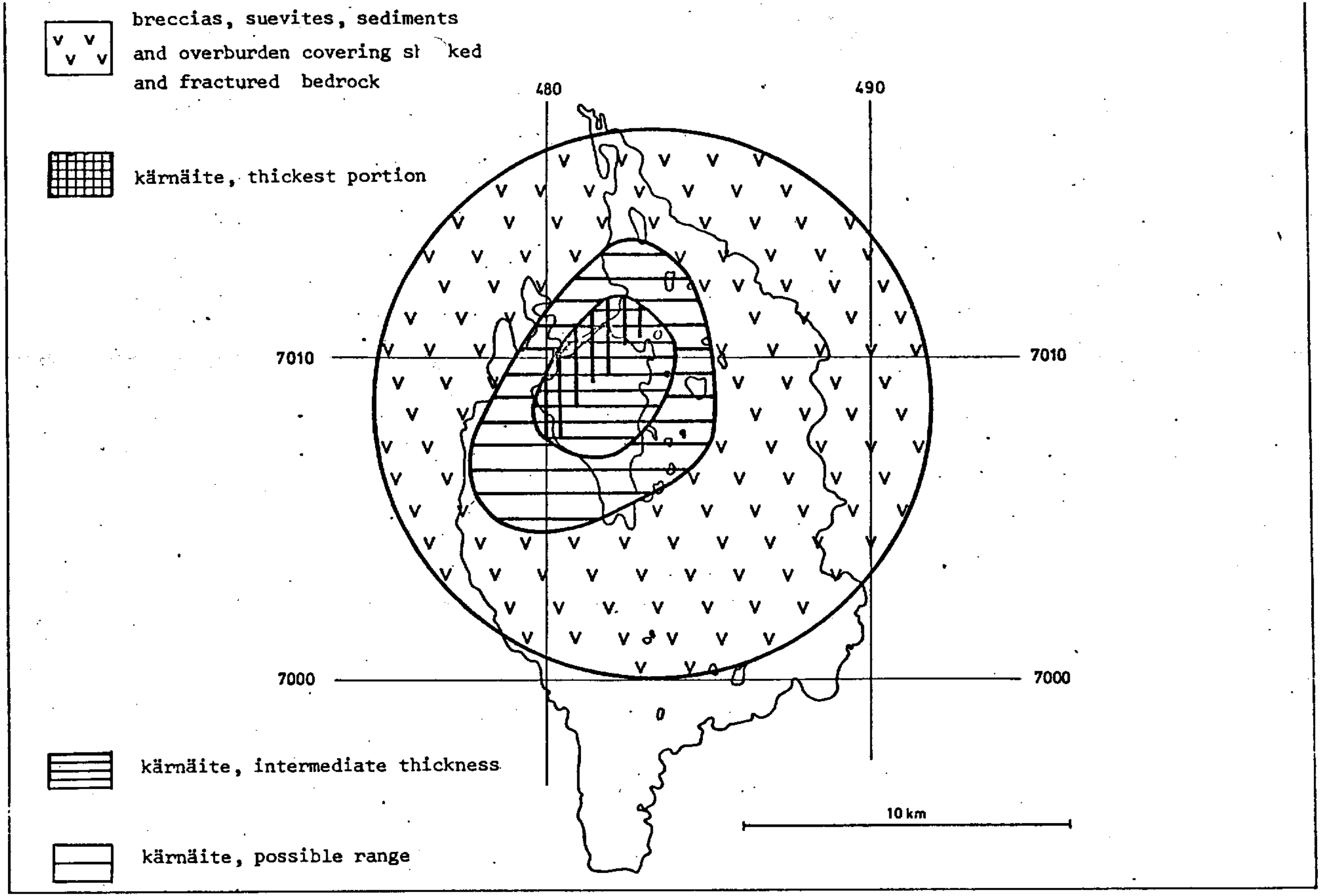


Figure 10. The interpretation of the positive residual anomaly based on the hypothesis 1.

Hypothesis 2: the residual anomaly is caused entirely by a central uplift. Two cross-sections of the interpretation model are shown in Figure 9. The contrast of +0.16 g/cm^3, which approximately equals the difference in densities of shocked bedrock and suevite&impact breccia, gives an uplift of about 0.5 km. The result of the interpretation is outlined in Figure 11.

The true structure is certainly much more complex than either of the models, but may be in principle a combination of the both. One such combination (kärnäite and shocked bedrock surrounded by low density breccias) is shown in Figure 12.

The cross-sections of the models in Figures 8, 9 and 12 were obtained by means of two-dimensional interpretation procedures. In Figure 13 the anomalies calculated for two- and three-dimensional prisms sharing common cross-sections are compared.

CONCLUSION

The available geological information and the interpretation of the gravity anomalies together suggest that Lake Lappajärvi is or resembles a complex hypervelocity impact crater. In addition to the general structure, estimates of approximate dimensions of units defined by apparent mean density contrasts were obtained. However, the inverse problem of potential field theory (e.g. deriving density distributions from gravity anomalies) is inherently ambiguous. Therefore, besides the errors of reduction, interpolation, regional-residual separation and interpretation procedures, the quality of models is also dependent on the available complementary data (e.g. rock densities and geological information).

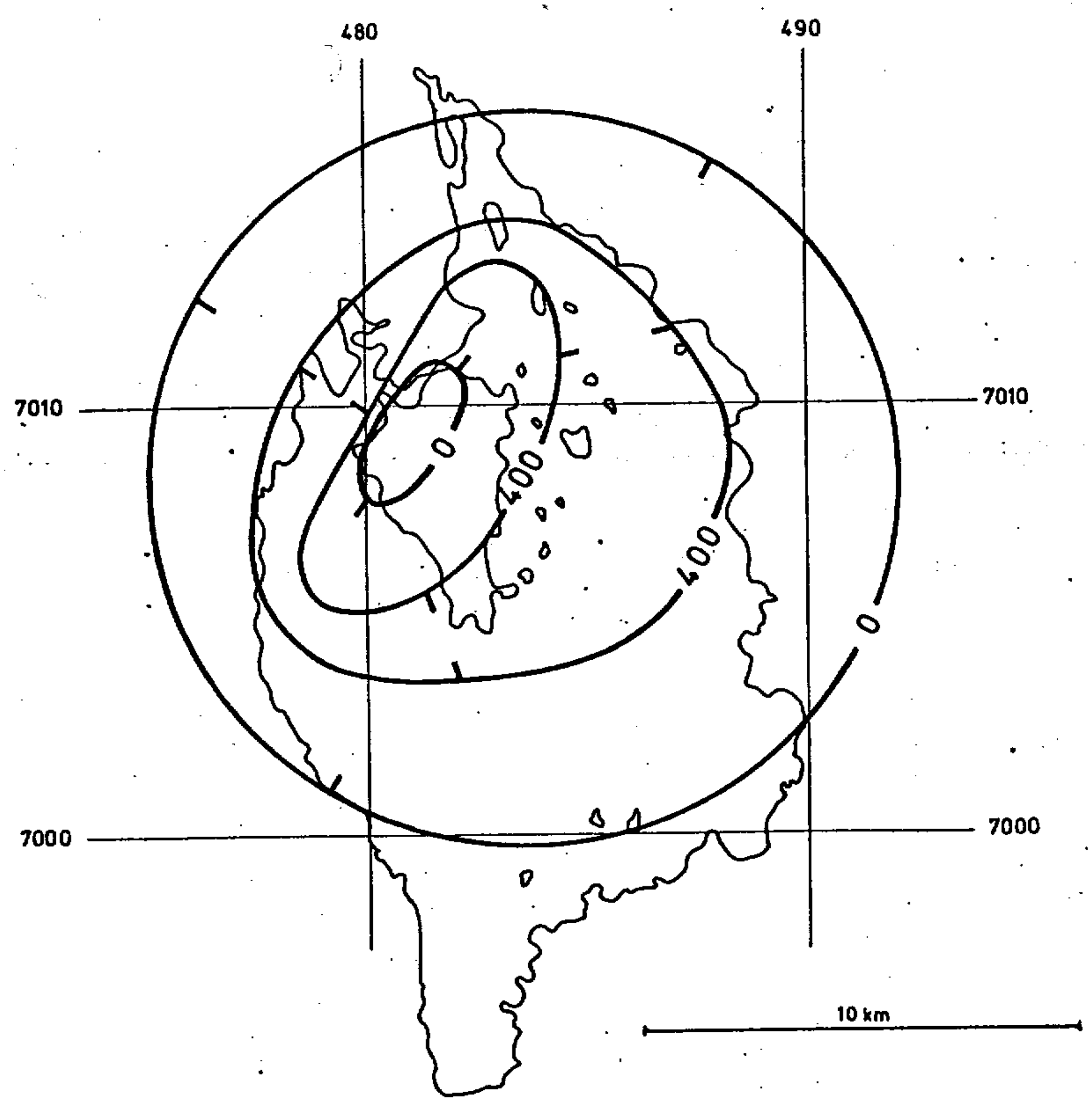


Figure 11. Outline of the central uplift defined as a surface between two units the mean density contrast between which is 0.16 g/cm^3. The contour interval is 400 meters.

Figure 12. An interpretation of the positive residual anomaly.

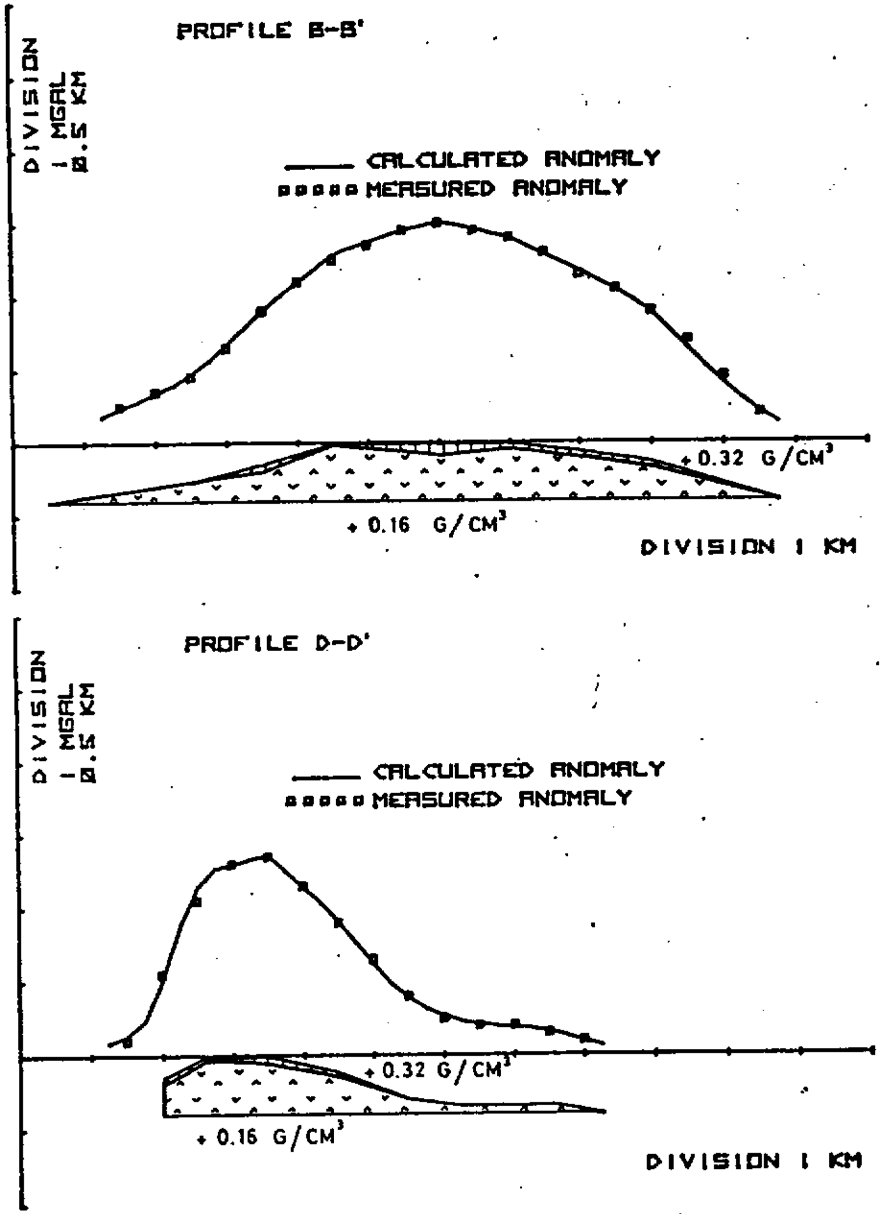
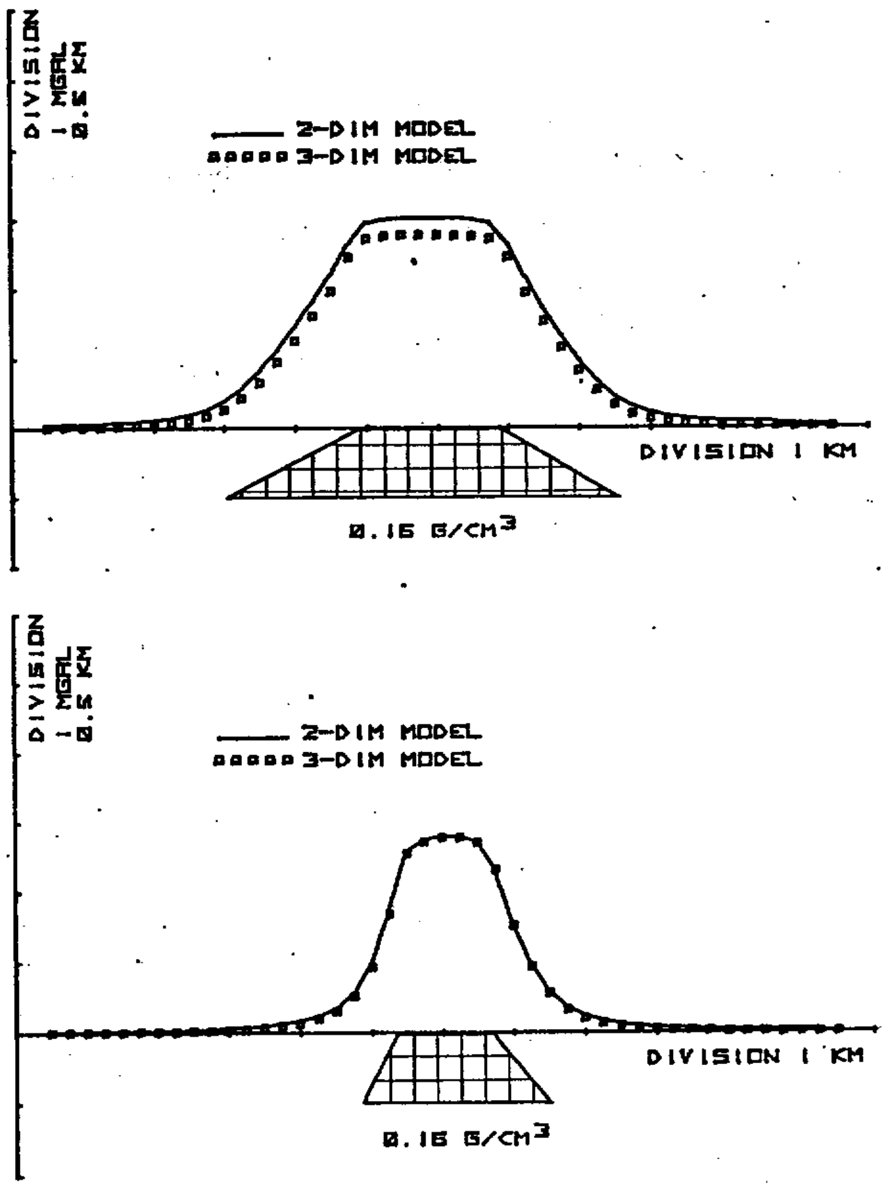


Figure 13. A comparison of anomalies calculated for the 2- and 3-dimensional prisms sharing the displayed cross-sections that are perpendicular to each other.



ACKNOWLEDGEMENTS

I feel indebted to Dr. Siikarla for initiating my study, to Lic. Phil. Pipping for supplying the material for the density determinations and for geological information, to the petrophysics group of the department of geophysics for preparing the density data, to the field crew of the same department for carrying out the gravity measurements, and to several other persons not mentioned here.

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