Separate gravimetric and magnetic anomaly sources: deep Permian intrusions at Nes, Hedmark

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A broad elongated aeromagnetic anomaly striking N40E occurs in the central part of the Mjøsa district at Nes and Brumunddal, southern Norway. Previous magnetic investigations from the area have indicated a source depth of about 1700 m. The source was assumed to be a Permian pluton consisting of larvikite, because of the rhomb-porphyry situated north of Brumunddal. Magnetic modelling, using a typical susceptibility of larvikite, gives a depth of about 2500 m. A small local anomaly that strikes across the main anomaly in the western part of the Precambrian gneiss complex of the horst at Liberget–Solbergåsen is found to be associated with vertical magnetic layers in the Solbergåsen rock complex. The magnetic layers are assumed to be granodiorite. A residual gravity anomaly map constructed based on old and new gravity data shows a negative anomaly associated with the eastern part of the horst, Liberget, which contains granite. It is probable that the horst continues across Furnesfjorden and further east. The main aeromagnetic anomaly has a strike that differs from that of the gravimetric residual anomaly, indicating separate magnetic and gravimetric sources. The western part of the horst, Solbergåsen, is associated with a small positive gravimetric anomaly. The Furuberg Formation situated south of Solbergåsen has a low density and is associated with a small negative anomaly. The gravity modelling gives fairly shallow sources.

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The aeromagnetic map of the central part of the Mjøsa district (NGU 1981) shows a broad and positive magnetic anomaly with an amplitude of about 250 nT (Fig. 1). The elongated anomaly coincides with the horst at the Nes peninsula, but is broader and continues through Brumunddal.

The aeromagnetic map also shows a small and local anomaly in the western part of Solbergåsen at Solbjør, with an amplitude of about 100 nT striking across the general trend of the main anomaly. This small anomaly has a strike like the schistosity of the crystalline rocks of Solbergåsen. The strike is also parallel to the magnetic lineations southeast of Mjøsa in the Precambrian outside the Oslo graben (not shown in Fig. 1).

The main aeromagnetic anomaly has previously been interpreted as caused by a deep Permian pluton (Åm 1975, 1976) that is assumed to be larvikite because of the rhomb-porphyry situated north of Brumunddal. Rhomb-porphyry is the extrusive rock of larvikite. Permian intrusions dominate south of the Mjøsa district in the Oslo graben system.

Geological setting

The central part of the Mjøsa district is dominated by Cambro-Silurian sediments. Precambrian rocks outcrop as a horst across the Nes peninsula. The horst had its latest development in Permian time (Skjeseth 1963). Permian rhomb-porphyry and Permian Brumunddal sandstone occur north of Brumunddal and west of the Brumunddal fault. Here, Permian rhomb-porphyries and sandstones juxtapose the Eocambrian rocks to the east (Rosendahl 1929; Skjeseth 1963; Høy & Bjørlykke 1980). The eruption of the rhomb-porphyry can be seen in connection with the development of the horst (Rosendahl 1929). The rhomb-porphyries are of the same type as those of the Oslo graben.

The Middle Ordovician Furuberg Formation contains sandstone and shale. The Hovinsholm Shale and the Bjørge Formation (upper didomygraptus shale, Middle Ordovician) are located south and north of Solbergåsen, as shown on the geological sketch (Fig. 2).

Permian faults have split up the area into blocks with relative vertical movements.

Field survey

Several gravimetric and magnetic ground profiles were run across the Nes peninsula and surrounding area. Eighty-four gravity stations were established, and rock samples for density determination and magnetic mineral identification were collected.

Gravity data

In 1969, Åm & Sindre (NGU) measured 138 stations at 200 m intervals east of Lake Mjøsa and covering ca. 27 km along the railway line from Hamar to Vestheim. These data have been made available to us. Some additional gravity stations have been established by Ramberg (1976). During two surveys, 84 new gravity stations have been relatively measured at Nes peninsula (Fig. 3).

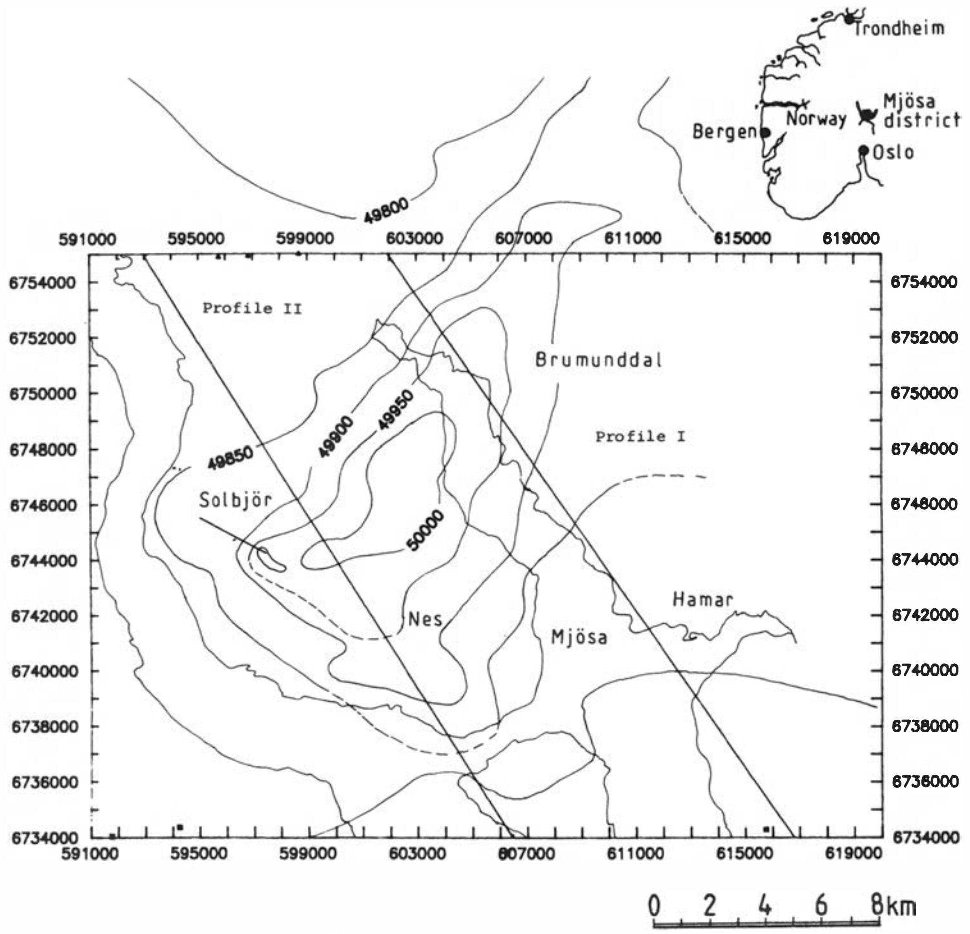

Fig. 1. Section of the aeromagnetic map (Hamar 1:250000). Field values in nT. Magnetic profile lines I and II are shown. Map coordinates in UTM (zone 32V). Insert gives location of Mjøsa district in southern Norway.

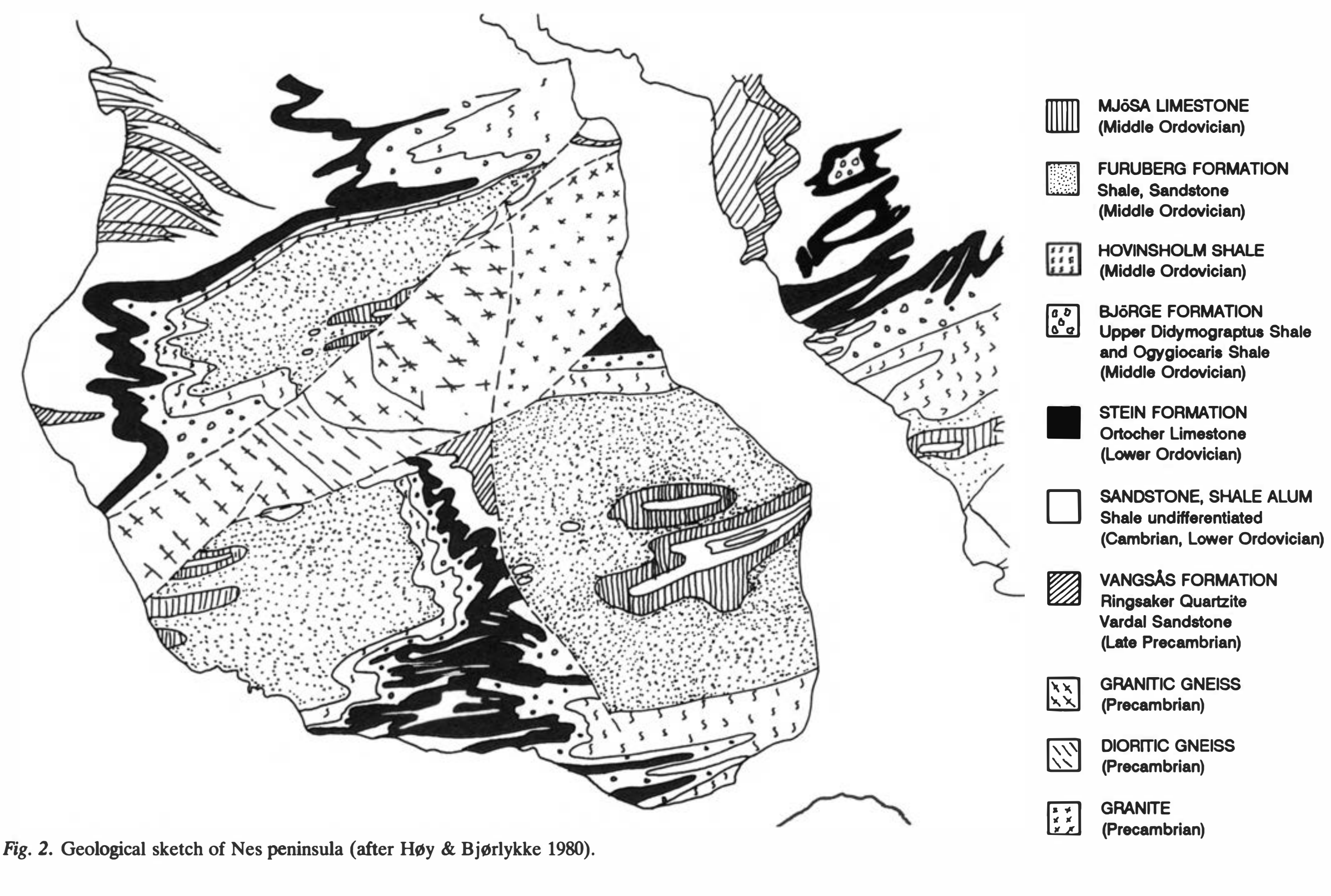

Fig. 2. Geological sketch of Nes peninsula (after Høy & Bjørlykke 1980).

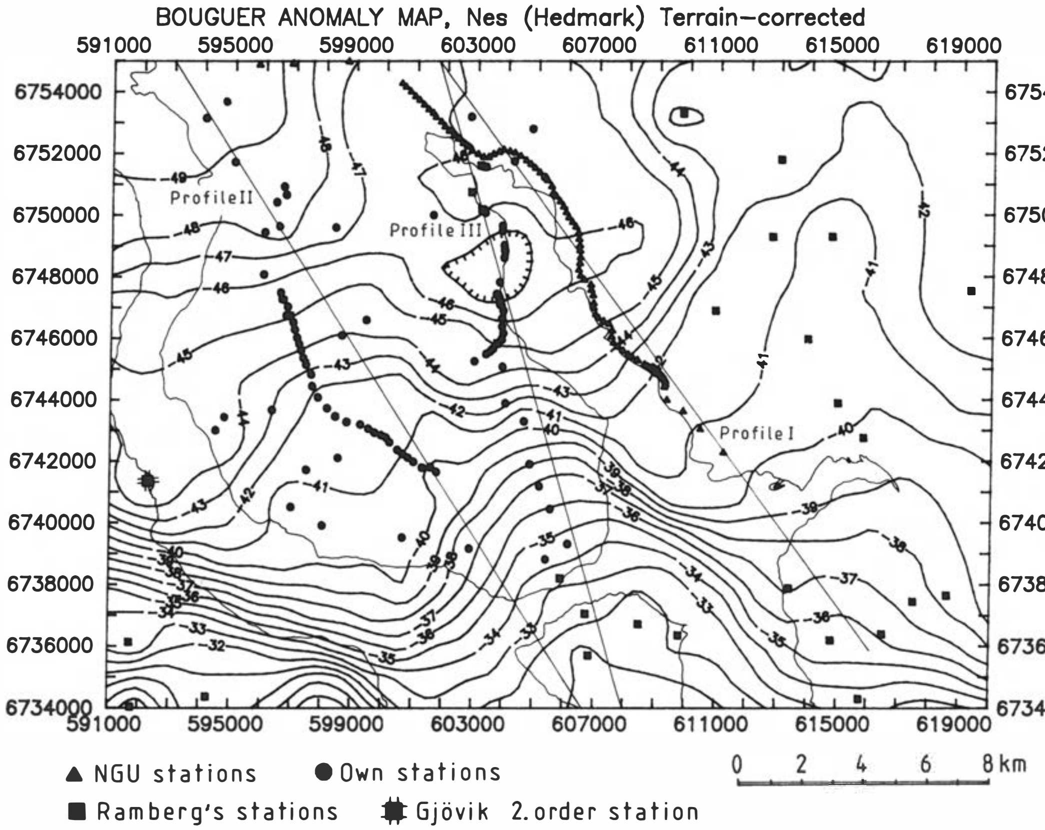

Fig. 3. Bouguer anomaly map, unit:mgal, with locations of gravity stations and profile lines I, II, III.

The stations were measured using a Lacoste Romberg gravimeter (no. 214), which has a small and constant drift (ca. 1 mgal per year); the variations during the day are generally caused by tidal effects (Ramberg 1972). Two measurements were made at each station. The accuracy of the readings is estimated at ±0.009 mgal and is based on the average absolute difference for the pairs of readings. The horizontal positions were obtained from the 1:5000 map.

Elevation control

The gravity stations east of Liberget were positioned at fixed points established by the local road authority. The stated elevation error is ca. ±10 cm.

The gravity stations across Solbergåsen at profile II were determined by levelling between two fixed points. The levelled elevation difference between these fixed points was within the stated accuracy, so we assume that the levelling of the other stations has the same accuracy, i.e. ±10 cm. The other elevations at the stations at Nes were taken out of the 1:5000 map from the 5-m contours. The error is estimated to be less than ±0.5 m.

Magnetic data

Twenty-six samples collected from the horst by Åm for susceptibility measurements are regularly spaced. The measurements were carried out on powder and on cores.

Susceptibility measurements in the field at Solbergåsen were made using a Bartington MSI susceptibility meter. In the Solbjør area, oriented cores were drilled, and *in situ* susceptibility measurements were made when surveying the local anomaly.

Measurements of the total magnetic field intensity were made using a Geometrics G 816/826 proton magnetometer with the sensor 2 m above ground level. Normally, the distance between measured points was 25 m, but for the local anomaly a spacing of 10 m was used.

Gravity reductions

The gravity data were corrected at the Norwegian Mapping Authority using their software. The tidal effects were removed and all the relative gravity values were made absolute by connecting them to the Gjøvik second order base station. The data were corrected using the formula:

$$\delta g_b = (g + g_f - g_b + T_c) - g_0 \quad \text{or}$$
$$\delta g_b = (g + 0.03086\text{h} - 0.04185\text{h}\sigma + T_c) - g_0.$$

Here g is the observation at the station, g_f the free-air correction, g_b the Bouguer correction, T_c the terrain correction and g_0 is the theoretical gravity value based on the international gravity formula from 1967 (Stacey 1977). Some of the stations measured near water masses are corrected for gravity effects caused by the lake. The reduction programme is described by Røthing (1989).

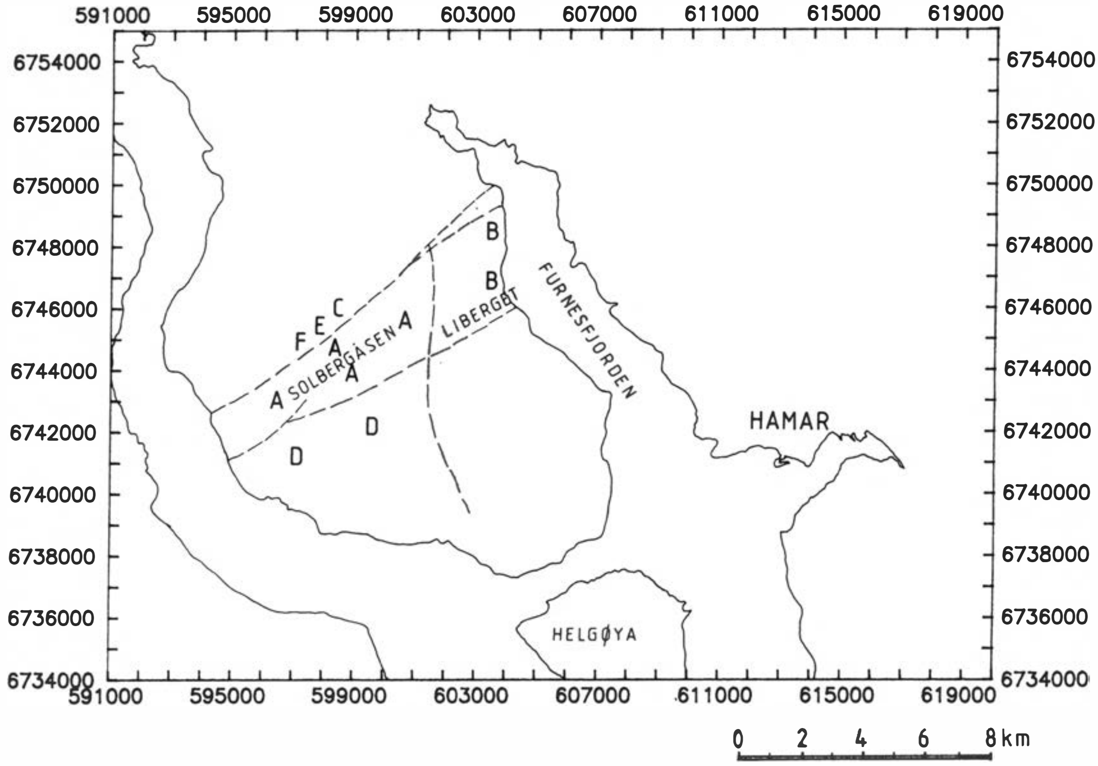

Fig. 4. Map showing locations of density sampling sites. Table 1 gives an explanation of the letter codes.

Densities

Two methods of estimating rock densities have been used as an aid to the physical and geological interpretation. One-hundred-and-twenty-seven rock samples were collected from the area for density measurements. They were kept in water for 24 h, then hand-dried and weighed in air and water to an accuracy of $\pm 0.003\ g/cm^3$. This accuracy is based on two weighings of the samples. The density localities are shown in Fig. 4.

The horst in this area, Solbergåsen–Liberget, is made up of precambrian rocks. Solbergåsen contains dioritic and granitic gneiss and Liberget contains granite, usually with augen feldspar (Høy & Bjørlykke 1980).

Outside the horst the geology is dominated by Cambro-Silurian sediments containing various lithologies. The rocks north and south of Solbergåsen are mostly Middle Ordovician sandstone and shale (Skjeseth 1963; Høy & Bjørlykke 1980). Forty-nine of the 126 rock samples are from six different localities within the Cambro-Silurian sedimentary sequence north and south of the horst (Fig. 4); 25 samples were taken from the Furuberg formation (shale and sandstone), locality D; 15 samples from the Hovinsholm Shale, locality E; and 9 samples were taken from the Bjørge formation, locality F. The density data for all localities are summarized in Table 1.

The other method used in density determination is the Nettleton density test (Nettleton 1939). The density of a homogeneous thick layer along gravity profile III, south of Liberget (horst), is estimated by this method. Application of this method is used when the topography varies and there are no vertical faults. The gravity measurements south of Liberget (profile III) that cross the Cambro-Silurian deposits there have an elevation difference of about 200 m. The density was estimated at $2.8\ g/cm^3$.

Bouguer anomaly map

Figure 3 shows the Bouguer anomaly map from the area with 1 mgal contour interval. The map is based on 242 gravity stations (96 from NGU, 67 from Ramberg (1972) and 79 are our own stations). The map is in the UTM coordinate system (zone 32V).

The Bouguer anomaly map in Fig. 3 should be compared with the Bouguer anomaly map of the Oslo graben system presented by Ramberg (1976). His 5-mgal contoured anomaly map covers the Mjøsa district (the field area) in its northern part.

Table 1. Average densities from the field area.

Rock type	Locality code	No. of samples n	Mean density g/cm^3	S.D.	Range g/cm^3
Gneiss, Solbergåsen,	A	30	2.669	0.075	2.535–2.832
Granite, Liberget	B	18	2.608	0.029	2.559–2.680
Mjøsa Limestone, Bratberg	C	22	2.718	0.038	2.664–2.828
Furuberg Formation	D	25	2.625	0.045	2.491–2.700
Hovinsholm Shale	E	15	2.665	0.006	2.665–2.676
Bjørge Formation	F	9	2.649	0.020	2.623–2.673

Our Bouguer anomaly map (Fig. 3) shows large gravity gradients in the south. From the middle of the map and northwards, the gradients are more gentle. At Liberget and to the east of Furnesfjorden a local gravity low is revealed.

The large gradients to the south can also be seen in Ramberg's map (1976) of the Oslo graben system. According to Ramberg, this long-wave, broad anomaly has an axis that trends through the Oslo graben system in a NNE direction. The source of the anomaly is interpreted as crustal thinning or deep formations in the crust above Moho (Ramberg 1976).

South of the Nes peninsula the map shows a marked gravimetric ridge. Mjøsa limestone outcrops to the southeast at Nes as seen on the geological sketch (Fig. 2). The Mjøsa limestone has an estimated density of 2.72 g/cm^3, which is significantly higher than the Cambro-Silurian deposits. The gravity ridge is relatively broad and is difficult to explain in terms of the Mjøsa limestone alone.

Separation of the regional and residual field

There are several methods in the literature for separating anomalies from the regional field. The regional field is by definition a smooth curve. Some of the methods are analytical (Dobrin 1960; Nettleton 1976) and others are graphical. The graphical methods are subjective and empirical, but they are quite useful when the information about the surface geology of the area is good. Graphical methods are used here and Ramberg's presentation of the Bouguer anomaly map was utilized as an aid towards acquiring a regional picture.

Residual anomaly map

The Bouguer anomaly map was digitized on a 23×31 grid system by an automatic contour/grid programme using a 5000 m search radius and weighing the surrounding data points with the inverse of the distance squared. The 31 north–south trending gridlines were plotted and smoothed by hand, these smooth profiles then forming the basis of the digitized (23×31) regional map.

The residual field is the result of subtracting the regional field from the Bouguer anomaly map (Fig. 5). The steep gradients to the south have disappeared. The negative anomaly has become clearer and it has an elongated feature that strikes N45E. A weak positive anomaly is located at Solbergåsen.

Gravity profiles and modelling

The gravity stations are projected onto three profile lines shown in Fig. 3. Gravity profile II goes from coordinate point (6755000, 593000) and runs in a direction N148E. It contains stations across Solbergåsen and southwards

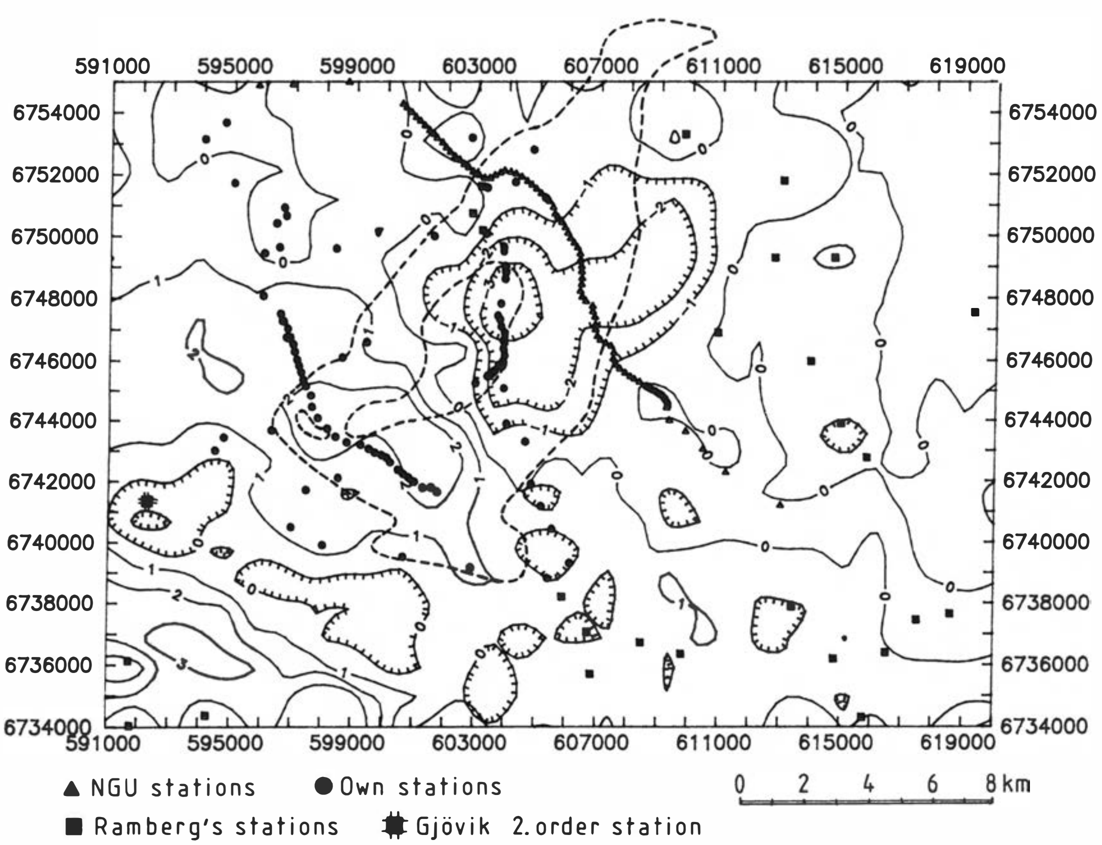

Fig. 5. Anomaly map. Solid lines: residual gravity anomalies, unit:mgal. Dashed lines: total magnetic anomaly.

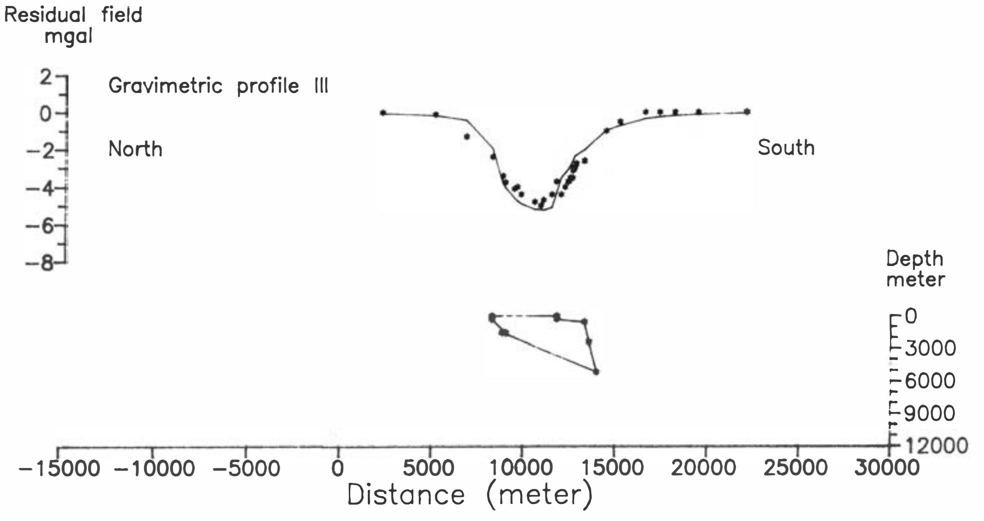

Fig. 6. Gravimetric profile III and model. Depths and distances in m. Solid curve: model calculation. Profile line goes from north to south.

to Helgøya. Profile I, going from point (6755000, 602000), runs in a direction N144E and contains stations along the railway line to Hamar. Profile III starts from the same point as profile I, but the direction is N164E. The northern part of the profile has the same set of stations as profile I, but from Liberget and southwards new stations were projected onto the line. The regional field for each line is taken from the gridded regional map. The gravimetric modelling was done with a 2.5 D programme, and the bodies were made as simple as possible based on the available geological and geophysical information. The density of the Precambrian rocks has been set to 2.67 g/cm^3. This is the average density of samples from the Solbergåsen rock complex.

Anomaly field, profile III

Gravity profile III runs transverse to the horst at Liberget. Cambro-Silurian sediments are situated to the north and south of the horst. The geological map (Høy & Bjørlykke 1980) shows a geological profile near the gravimetric profile line, indicating the thickness of the various Cambro-Silurian layers. The locations of faults used in the geophysical modelling are taken from the geological map. Liberget contains granite, usually with augen feltspar, with an estimated density of 2.61 g/cm^3. The Cambro-Silurian layer (ca. 200 m) has an estimated density of 2.78 g/cm^3 and is included in the model but not shown in Fig. 6.

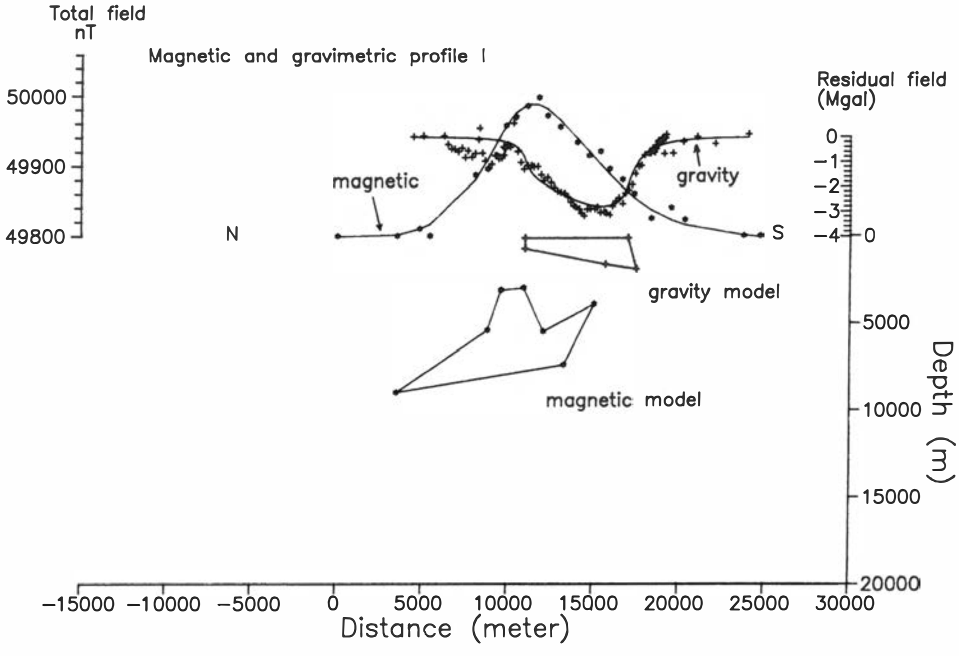

Fig. 7. Combined magnetic and gravimetric anomalies for profile I. +: gravimetric, *: magnetic. Solid curve: model calculation. Profile line goes from north to south.

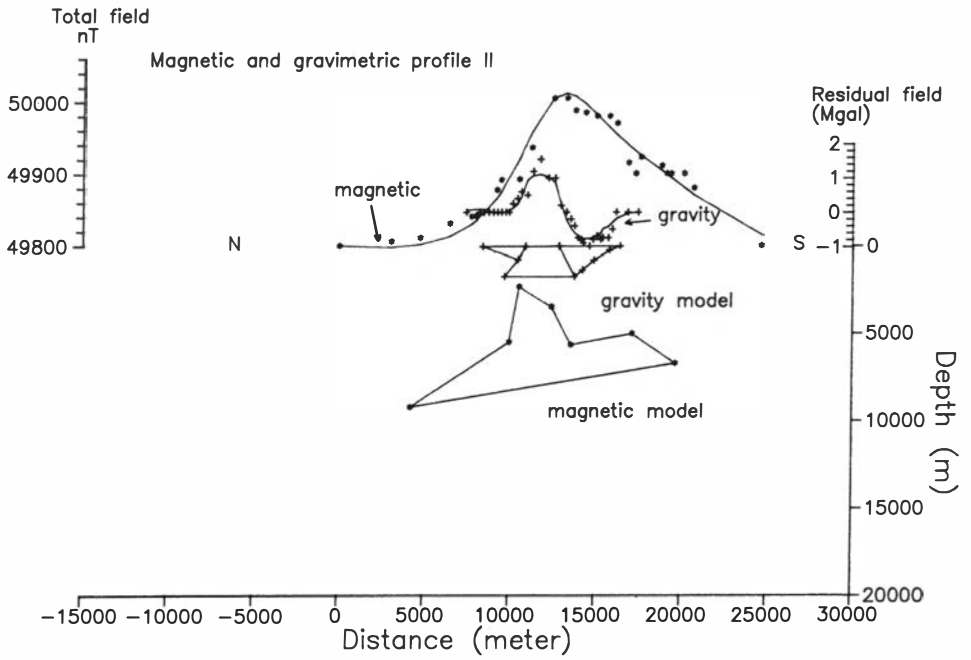

Fig. 8. Combined magnetic and gravimetric anomalies for profile II. +: gravimetric, *: magnetic. Solid curve: model calculation. Profile line goes from north to south.

Anomaly field, profile I

Figure 7 shows the interpretation of profile I. The body is given a density contrast of $-0.06\ g/cm^3$ relative to the assumed density of Precambrian rocks. This is the same density contrast as has been used for the granite complex at Liberget in profile III. The top of the body is fixed at a depth of 80 m, in accordance with data from well drilling in the Mjøsa quartz sandstone. Mud from that depth carries fragments of gneiss that most probably derive from the Precambrian bedrock (Skjeseth 1963).

Anomaly field, profile II

Gravity profile II, which is presented in Fig. 8, shows a small positive anomaly across Solbergåsen. South of Solbergåsen across the Furuberg Formation there is a negative anomaly.

The Furuberg Formation south of the horst has an estimated density of $2.63\ g/cm^3$, and the geological map indicates that the formation close to the horst consists of a thick layer of sandstone and shale which becomes thinner towards the south (Høy & Bjørlykke 1980). The model indicates that the formation is about 1.5 km in depth close to the horst. The Hovinsholm Shale and Bjørge Formation to the north of the horst are given a density of $2.66\ g/cm^3$, and the positive anomaly is then partly explained by the denser rocks in Solbergåsen. But the model in Fig. 8 also contains a body close to the horst in the north with a density of $2.64\ g/cm^3$, necessary to produce the steep anomaly flank. Inspection of the density data from the samples showed that the site just to the north of the horst was the only rock formation where a clear bimodal density distribution was found. The low density part is centred at $2.635\ g/cm^3$. We therefore consider it likely that there exists such a low density body to the north of the horst.

Magnetics

As mentioned earlier, the magnetic map shows two anomalies, a main one with approximately N40E strike, and a local one striking N140E (Fig. 1). The map also shows that the region to the east of the local anomaly is marked by other deviations from the pattern set up by the main anomaly. At the southern border of the main anomaly there are indications of another isolated anomaly. The measurements of the total magnetic field were made at about 150 m constant height above ground by E-W flight lines, with about 500 m between lines.

The region has also been surveyed on foot; however, we were forced to run the lines where the area was accessible. The description of the magnetic investigation will be split into two parts, one dealing with the main anomaly and one discussing the local anomaly and its possible relation to the main system.

The main magnetic anomaly

Some synthetic profiles were constructed from the aeromagnetic map. An unpublished supplementary map where selected field values are plotted along each flightline was also used. Figure 1 shows the location of magnetic profiles I and II, chosen to coincide with the corresponding gravimetric profiles and therefore not necessarily perpendicular to the magnetic strike.

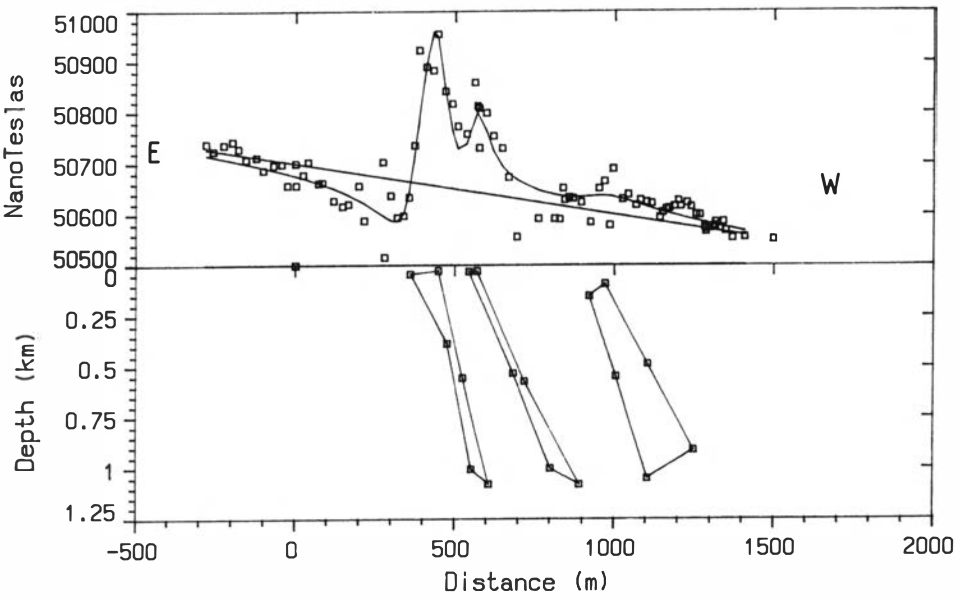

Fig. 9. Ground magnetic profile for the local anomaly and model. Solid curve: model calculation. Straight inclined line gives the regional field variation. Profile line goes from east to west.

The magnetic field to the north of the anomaly is fairly constant, with a value of about 49800 nT. To the south, the anomaly is well separated from the northern border of the Oslo graben anomaly pattern, and the largely undisturbed field here is also about 49800 nT. It is therefore reasonable to use a constant regional field in the modelling. However, the modelling gave more realistic results when the regional field increased slightly northward, by 20 nT over the profile length.

In situ susceptibility measurements yield predominantly low values around 0.00015 (SI). This value was confirmed by laboratory measurements on rock samples.

The data from the magnetometer on the ground indicate the presence of stronger magnetic material close to the surface, since the ground profiles appear noisy with occasional 50–100 nT peak-to-peak amplitudes, often with the full variation between nearby sample points. Figure 9 gives a typical example where the main anomaly can be seen as the regional field. Similar features can also be seen in Figs. 7 and 8, indicating that the higher magnetization extends to some depth. It is not likely, therefore, that the aeromagnetic anomaly represents the integrated effect of a variably magnetized surface layer. But only in connection with the local anomaly have we been able to measure substantial susceptibilities.

The average measured susceptibility is therefore not suitable for modelling. A possible value can be found in the studies of the larvikite complexes in the Oslo region (Kristoffersen 1973; Åm & Oftedahl 1977), which give values of about 0.025 (SI) but with large deviations to either side. There is ample evidence in the cited papers that the susceptibility is accompanied by a significant remanence. Hence a ratio between the natural remanence and the induced magnetization (the Koenigsberger Q ratio) as high as 1.5 is not unreasonable. It is to be expected that the effective magnetization will be reduced, however, as the remanence can have a varying direction. The modelling has therefore been performed with susceptibilities of both 0.025 and 0.038, the latter value simulating the effect of a Q ratio of 0.5 with the remanence along the present field.

Both values give reasonable solutions for the depth to the magnetized body; Figs. 7 and 8 show the results for profiles I and II when 0.038 is used for the susceptibility. Increasing the susceptibility further produced bodies with sharp peaks or strong thinning towards the top. We take this as an indication that the real magnetization corresponds to susceptibilities not larger than 0.038 (SI).

The minimum depth to the body is 3000 m below the surface in profile I and 2500 m in profile II. The maximum depth (which in general is difficult to determine) is about 9000 m for both profiles. The body in profile II has a rather broad basis, in good agreement with what can be seen in the aeromagnetic map, as the main anomaly gets broader from profile I to II, indicating that the body has a larger horizontal extent in the SW.

The results of the modelling indicate that the magnetic body is fairly deep, with a minimum depth of 2500 m. This is not in agreement with the results of earlier investigations, where a depth of about 1700 m was found (Åm 1975, 1976). A possible explanation for the difference is that our body does not have the shape of a thick dyke or plate. Such a body would have to be fairly broad and be situated closer to the surface in order to match the anomaly.

The local anomaly

Three ground profiles were run across the anomaly. The observed values were corrected for time variations both by comparison with records from the magnetic observatory at Dombås (situated about 160 km to the NW) and by repeated measurements at a control point. Copies of the original in-flight recordings from the total field magnetometer for the appropriate flight-lines were also obtained.

It was difficult to find rock outcrops from this region because of the thick cover and forest; accordingly, *in situ* susceptibility measurements are sparse. Of the nine sites where samples could be taken, only one gave a significantly higher value than the normal value of 0.00015 (SI). This sample showed a susceptibility of 0.032 (SI) and was located just outside and to the NE of the 50000 nT contour of the local anomaly in Fig. 1. The minerals in the rock sample have been identified in thin section and the sample is classified according to the Strekheisen scheme as a granodiorite (pers. comm. O. F. Tjugen). The geological map of the area shows this rock type to be common east of the local anomaly in the horst. This site was also the only one where a correspondingly high *in situ* susceptibility was found. All samples gave low values for the remanence (Q ratio less than 0.1).

Magnetic modelling

Figure 9 shows the result of the modelling based on one of the ground profiles projected on a line normal to the magnetic strike at N130E. Note that the regional field at about 50600 nT is higher than shown in the aeromagnetic map. This is due to the secular variation between the years 1965 and 1989.

It could be seen from the data alone that the source is divided into a number of nearly vertical bodies, and it is clear that a detailed model must include a multitude of thin sheets to give an "exact" fit. The main objection to the chosen model is, perhaps, that is does not accommodate the minimum at distance 700–900 m. A recalculation at the 150 m flight level, however, gave good correspondence with the aeromagnetic data. A model with an undulating surface layer of variable susceptibility and a few hundred metres thickness was also tried, but gave no satisfactory fit.

The modelling indicates that the local anomaly is caused by a suite of nearly vertical bodies with a susceptibility of about 0.03 (SI), with depths in the range <10 m to about 30 m. This does not allow for any outcropping bodies having the high observed susceptibilities. These bodies can be followed from profile to profile, which shows that the magnetic strike of the rocks in question is along the schistosity. The bodies extend down to about 1000 m.

It is therefore not likely that the local anomaly is caused by dikes extending upwards from the causative body of the main anomaly. A more probable explanation is that there are two separate sources for the two anomalies, and that the local anomaly is due to vertical magnetic layers in the Solbergåsen rock complex.

It is reasonable to assume from the analysis of the rock samples that the local anomaly is associated with the granodiorite. This argument is also supported by the existence of local magnetic variations further to the east into the mapped region for the granodiorite.

Discussion and conclusions

It is of particular interest to compare the results from the gravimetric and magnetic modelling, as shown in Figs. 7 and 8. The modelling indicates that the sources for the two fields are quite separate, with the gravimetric sources on top of the magnetic. Profiles I and III give a definite depth for the bottom of the gravimetric body, while in profile II the modelling has in reality been a modelling of the effect of the lateral density contrast only, as the horst here is assumed to have the same density as the homogeneous rocks below. Profile II therefore gives no indication of the depth extent of the horst at Solbergåsen.

An independent confirmation of the separation of the two sources can be found from the geophysical map in Fig. 5. The magnetic anomaly has a clearly different trend from the suite of positive and negative gravimetric anomalies. The angle between the trends is about 20–30°, with the magnetic anomaly trending more northwards. This also indicates that the sources are not connected.

It has not been possible to see an effect in the gravimetric data from the magnetic body, although the profiles should have sufficient length to allow this. This means that the density of the deep magnetic rocks is about 2.67 g/cm^3, the same density as the rocks in Solbergåsen.

In the magnetic modelling, however, we have used susceptibilities indicative of larvikite-like rocks, mainly because of the rhomb-porphyries in Brumunddal (Rosendahl 1929). This has given fairly deep sources, especially when a probable remanence (Q ratio = 0.5) is taken into account. The depths are larger than earlier estimates, and setting Q = 0 does not change this.

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