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Structure of the Jotun Nappe Complex, Southern Norwegian Caledonides: Ambiguity of Gravity Modelling and Reinterpretation.

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Structure of the Jotun Nappe Complex, Southern Norwegian Caledonides: Ambiguity of Gravity Modelling and Reinterpretation

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Sammendrag:

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The astonishingly close correlation between surface geology and gravity and magnetic maps provide constraints on the gravity modelling. These constraints, in combination with new petrophysical data and an alternative regional-residual gravity separation, lead to a new geophysical model in agreement with the hypothesis that the Jotun Nappe was transported over a considerable distance from the northwest onto the Baltic shield.

The emplacement of the dense Jotun rocks onto the Precambrian crust must have caused gravitational instability and regional isostatic adjustments associated with vertical tectonics. Gravitational subsidence provided a mechanism to preserve the thickest part of the massif in a depression or a half-graben to the north of the Lærdal-Gjende fault. These adjustments within the upper lithosphere could be post-orogenic in nature and might be associated with extensional faulting.

Included in the report is a discussion of the errors associated with the estimation of average densities.

Emneord	Gravimetri	
Geofysikk	Petrofysikk	
Magnetometri	Geologi	Fagrapport

STRUCTURE OF THE JOTUN NAPPE COMPLEX, SOUTHERN NORWEGIAN CALEDONIDES: AMBIGUITY OF GRAVITY MODELLING AND REINTERPRETATION.

JAN REIDAR SKILBREI

ABSTRACT

Gravity studies have previously indicated a deep root zone (16 km thick) below the outcropping pyroxene-granulites of the Jotun Nappe Complex in southern Norway. Combined interpretation of gravity and aeromagnetic data give results that contradict these earlier gravity interpretations. The Jotun Nappe Complex is inferred to be less than 6 km thick at the deepest part, and the thickness changes abruptly across the Lærdal-Gjende fault which is clearly reflected in the magnetic and gravity maps. The Lærdal-Gjende fault penetrates at least down to the maximum depth of the Jotun Nappe Complex and continuous further to the east than previously recognized.

The astonishingly close correlation between surface geology and gravity and magnetic maps provide constraints on the gravity modelling. These constraints, in combination with new petrophysical data and an alternative regional-residual gravity separation, lead to a new geophysical model in agreement with the hypothesis that the Jotun Nappe was transported over a considerable distance from the northwest onto the Baltic shield.

The emplacement of the dense Jotun rocks onto the Precambrian crust must have caused gravitational instability and regional isostatic adjustments associated with vertical tectonics. Gravitational subsidence provided a mechanism to preserve the thickest part of the massif in a depression or a half-graben to the north of the Lærdal-Gjende fault. These adjustments within the upper lithosphere could be post-orogenic in nature and might be associated with extensional faulting.

INTRODUCTION

Despite almost a century of debate, the structure of crystalline rocks of the Jotun Nappe Complex (JNC) in the southern Norwegian Caledonides (Fig.1) is still a point of contention. Conflicting interpretations of e.g. Roberts (1977) and Banham et al. (1979) emphasized the existing problems. Bjørlykke (1905) interpreted the JNC to be tectonically emplaced, while Goldschmidt (1916) indicated that the JNC was emplaced during northwestward and southeastwardly thrusting out of the 'Faltungsgraben', which is the synclinal basement depression trending northeasterly from the Hardangerfjord area, beneath the Jotunheimen mountains and into the Trondheim Region Caledonides (see Fig. 1). Holtedahl (1936) introduced the distant root hypothesis involving thrust emplacement of the Jotunheimen Massif onto the Baltic shield from the northwest.

The distant root hypothesis remained more or less unchallenged until gravity interpretations (Smithson and Ramberg 1970, Smithson et al. 1974) indicated a mass excess beneath the Faltungsgraben in the Jotunheimen mountain area, which was taken to represent the local root-zone. These gravity interpretation supported the hypothesis that a deep root zone exists below the present outcrop of the JNC, comparable to the Ivrea zone in the southern Alps. The gravity model for the nappe gave a maximum thickness of 16 km, and assumed an increasing density below the surface. It also include a hypothetical, "arbitrarily chosen", dense body within the JNC (Smithson et al. 1974). These authors suggested a mechanism involving upthrusting from below the present position rather than over-thrusting from a great distance to the northwest.

Battey and McRitchie (1973) supported the local root theory on the basis of petrological evidence. The composite nature of the massif was recognized, comprising a central tract of pyroxene-granulite facies gneisses enveloped by amphibolite facies gabbros on its southern and northern margins. These observations led Battey and McRitchie to propose that the pyroxene-granulites originated within the Faltungsgraben, and that it had been tectonically elevated and thrust outwards over the peripheral igneous rocks.

Recently, structural arguments have been advanced to support both schools of thought, and the gravity model displaying the JNC to extend down to 16 km has figured prominently in published studies. The discovery of a tectonic window within the JNC around Torfinnsbu (Emmett 1980), north of the lake Bygdin, close to the important Lærdal-Gjende fault (Heim et al. 1977, Milnes & Koestler 1985), indicated that the JNC is much thinner in that region than predicted by the gravity interpretations. Spectral analysis interpretation of aeromagnetic data was also in conflict with the gravity model as it gave a thickness of less than 5 km for the JNC (Aalstad et al. 1977).

It is the purpose of this paper to review earlier geophysical works by a careful analysis of the assumptions of the model calculations. In particular: the density data which is so critical to the resulting calculations is discussed, and new density data from the JNC and the surrounding gneisses presented. The problems of (1) assigning average densities to large 3-dimensional bodies by the sampling of a limited number of rock specimen at the surface, and (2) the statistical problem of estimating central tendencies of the sampled populations, are dealt with in detail due to their profound bearing on the final calculated gravity model. The ambiguity of gravity modelling is thus emphasized with the JNC as an example. The need to constrain the number of alternative model solutions is pointed out during the reinterpretation which combines gravimetric, magnetic and density data with knowledge of dips of geological contacts at the surface.

ESTIMATION OF DENSITIES

Gravity modelling is largely dependent on the applied density contrast and the interpreted magnitude of the residual anomaly. These parameters must therefore be considered very carefully. It is the purpose of this section to present new petrophysical data and to compare it with published data that have been the basis for earlier gravity studies in the region. Important aspects of the sampling of representative rock types and its influence on the statistical estimation of average densities will also be discussed.

The problem of estimating average densities.

To assign mean densities to rock groups by the sampling of a limited number of rock specimen is a very uncertain procedure. Errors can be, and normally will be, introduced at all levels. Sample errors are the most common and serious error. The sampling of the rock types that are the most representative for the rock unit one wishes to estimate the average density of requires a thorough knowledge of the geology of the area. Therefore, the sampling will normally be biased. To estimate the bias itself is seldom possible except in those cases where a statistical sampling procedure is applied (which requires a vast number of samples). In addition, the density variation with depth is estimated by samples taken at the surface.

The precision of the density measurements is within acceptable limits when personal bias is avoided in the laboratory, and the laboratory error will normally be negligible relative to the overall variation in the data set (Skilbrei 1988a). The closeness of the calculated mean value to the true value of the mean of the sampled data depend on the number of samples, the distribution of the sampled populations, and the statistical method employed to estimate the central tendency. Locally, geological data tend to show normal distribution, whereas regional data tend to be lognormally distributed. The lower density limit in crystalline rocks lies just above the microcline mineral density of 2550 kg/m^3 as this mineral is the most common lowest density mineral in crystalline rocks. The upper limit is well above 3300 kg/m^3. Consequently, regional sampled density data will often show frequency distribution with a positive skewness. For observations that follow the normal distribution, the arithmetic mean often yield the best estimate of central tendency. For observations showing a skewed distribution it is not appropriate to use the arithmetic mean value, since this measure of the central tendency is very sensitive to outliers in the extreme positive end of the sample distribution, whether it be statistical outliers caused by sampling errors, personal errors introduced during measurements and processing, or natural variations due to the heterogeneity of geology. It is therefore often preferable to use the median value because it is less sensitive to outliers. Alternatively, logtransformation can be desirable to reduce dependency of error variance on the magnitude of means.

Petrophysidal data.

Smithson et al. (1974) obtained a mean density of 2860 kg/m^3 for 103 samples of the JNC which was used in the gravity model. 36 samples of gneiss south of the JNC gave a mean density of 2750 kg/m^3, and 15 samples of gneiss north of the nappe had a mean density of 2730 kg/m^3. A density of 2740 kg/m^3

was applied in the model for the gneiss surrounding the JNC.

E. Tveten and O. Lutro (both at the NGU), who are responsible for the compilation of the geological map sheet 'Årdal' (M 1:250 000), selected rock samples which they regarded to be the most representative samples for the average composition of the JNC, and for the composition of the gneisses to the north of the JNC. The percentage histograms and summary statistics for norite (jotunite) and for gneiss rocks is shown in Fig. 4a and Fig. 4b, respectively. The arithmetic mean value of the samples of gneisses (granitic to monzodioritic composition) was 2655 kg/m^3 (28 samples) with a standard deviation of 30. The median was 2652 (or 2660 because of equal no. of samples, see Fig. 4b). For the samples of norite the arithmetic mean value is 2903 kg/m^3 with a standard deviation of 122. The median value was 2882 kg/m^3. No ultramafic rocks were included in the calculation. L. P. Nilsson at the NGU provided me a number of rock samples from the JNC of which most were ultramafics that ranged in density values between 3000 to 3460 kg/m^3. 9 gabbroic samples gave 2950 kg/m^3 as the arithmetic mean value. There is thus some discrepancy between different calculations which is commented on below.

Unfortunately, Smithson et al. (1974) do not report the standard deviation (st.dv.) of their measurements, nor the composition of their samples. It is thus not possible from the data they list to assess the data variation. In an earlier gravity study of the JNC, Smithson and Ramberg (1970) refer to a paper by Smithson (1963) who obtained 2740 kg/m^3 as the mean of 36 samples of Precambrian rocks south of the Jotunheimen. Even though the value for the 36 samples given in Smithson's 1963 paper (p. 113) and in Smithson and Ramberg (1970, p. 1573) is 2740, which is different from the figure 2750 given in Smithson et al. (1974), see above, it is reasonable to presume that these data all refer to the same 36 measurements. Bearing in mind the effect of incorporating samples with comparatively high densities in the data set used to estimate mean density of gneisses, we can now look at the original density data given by Smithson (1963), in the interest of drawing conclusions regarding the seemingly different values obtained from several data sets. (Tacitly, I have assumed that Smithson used the arithmetic mean value when estimating the mean, throughout).

The standard deviation of the 36 measurements was 0.121, with a range between 2620 and 3140 (kg/m^3), (Smithson 1963, p.113).

These 36 rock specimens were called "eastern gneisses" and are sampled from a local area to the east of the Flå Granite which is located well to the south of the Jotunheimen area, around 60 35'N, 9 45'E. On the geological map accompanying Smithson's 1963 paper (Plate 1), the only rock unit that is located to the east of the Flå granite is a "banded granodioritic gneiss, locally migmatitic; interlayered amphibolites". I therefore assume that the 36 samples were taken from these eastern gneisses containing amphibolites. The maximum value of 3140kg/m^3 probably represents an amphibolitic gneiss sample. Depending on the number of amphibolites included in the 36 specimen, the calculated mean value will be higher in value than if the gneisses contain only insignificant volumes of amphibolites. Even if it was right to incorporate amphibolite samples in this local study, and to assume this particular gneiss unit to be representative for the whole gneiss region to the south of the Jotun nappe, these high values represent statistical outliers which makes it inappropriate to use the arithmetic mean value as the estimate of central tendency of the sample population when there are only 36 observations. The population will show positive skewness and the arithmetic mean value will also show "positive skewness"; i.e. a higher value than the median value.

The mean density of 2740 kg/m^3 which has been assigned to the gneisses surrounding the Jotun nappe in earlier model calculations of the JNC is too high in value for several reasons discussed above. New estimates from representative samples taken from the gneiss area to the north of the JNC show that a density of 2670 kg/m3 is probably more correct. This value which is the 'normal' value for orthogneisses in the upper crust is consequently assigned to the gneisses surrounding and underlying the Jotun Massif. The 36 samples of Smithson et al. are representative of gneiss rocks rich in amphibolites. The area is located well to the south of the JNC and on the Bedrock map of Norway (Sigmond et al. 1984) this gneiss unit is only of local importance in the gneiss region to the south of the JNC. Thus, they are probably not representative of the area in question.

A mean density of 2860 kg/m^3 assigned to the Jotun nappe rocks is a reliable figure because of the comparatively large number of samples (103). This value for the density of the Jotunheimen pyroxene granulites is therefore used also in the gravity model presented below. However, some new density data indicate that a higher density could be used in the calculation of the density contrast, which would result in a shallower model for the Jotun nappe.

GRAVITY INTERPRETATIONS

The Bouguer anomalies over the Jotunheimen and its surroundings have been described at length elsewhere (e.g. Smithson et al. 1974, Ramberg & Grønlie 1977). A description of the gravity field will therefore not be given here. The gravity map of the Jotunheimen area is shown in Fig. 2 together with the area occupied by the outcropping JNC rocks.

The gravity and magnetic highs (see Fig. 3) and the gravity contours show an astonishingly close correspondence in area and outline with the outcropping JNC rocks (compare Figs 2 & 3). The so called Slidre gravity high (Smithson 1964) to the south of the Jotunheimen (north of Fagernes in Figs 2 & 3) coincides closely with the location of a magnetic high. There is little doubt that the outcropping rocks of the JNC must explain the gravity high above the area. The gradients in the gravity field outwards of the anomalous area are explained by the changing outcropping rock assemblages. The coinciding gravity and magnetic lows are located along the Sjodalen where metasedimentary rocks occur which occupy a tectonostratigraphic position below the JNC. This demonstrates: (1) The close matches between the gravity and the magnetic data. (2) The outcropping JNC rocks must explain each of the anomaly pictures. From these observations it would seem at first rather peculiar to interpret the existence of additional dense masses below the JNC. However, such interpretations depend also on the choice of the regional field. Because of the double lobe of the gravity field around Sjodalen, the residual gravity anomaly above the Sjodalen must be of weak positive amplitude or near zero. Thereby a shallower model will follow the calculation. If a rather strong positive anomaly is defined here as in the work of Smithson et al. (1974), than a deeper model will follow. Thus, such choices of the amplitude of the residual field and the modelling involve something of a 'circular argument': a large positive residual anomaly will be 'supported' by a deep body in the model calculation, and vice versa. This demonstrates the need to constrain the gravity interpretation in order to reduce the ambiguity. The new density data, which suggest that a comparatively thin body is causing the anomaly above the

JNC, together with the close similarities between the magnetic and gravity maps in terms of general anomaly picture, support a thin body model and thereby a low amplitude residual field above the Sjodalen.

Regional-residual separation.

The amplitude of the residual positive anomaly will partly determine the thickness of the body in the model calculation. The residual-regional analysis will therefore be dealt with in some detail. Smithson et al. (1974) calculated the gravity effect of the Moho , based on seismic work of Kanestrøm and Haugland (1971). They then assumed complete isostatic equilibrium, using an average crustal thickness of 33 km and a mantle density of 3320 kg/m^3. Another isostatic model was to assume that the compensation is achieved within the upper 40 km of the crust and mantle, and by applying a standard crust with mass per unit area of 11.840 kg/m^3 at a depth of 40 km they got an average value of 2880 kg/m^3 for the crust. It was decided on a regional gravity anomaly in between the calculate curves and the observed gravity profile. That is, the applied regional field was manually chosen (graphically fitted), and was thereby an arbitrarily chosen field in the 'sensu stricto' meaning. The main point is that the chosen regional trend curved downwards and made the residual anomaly higher in amplitude which lead to a thicker calculated model.

Deep seismic soundings have not established with certainty whether or not there exists a deep root zone beneath the central Scandinavian Caledonides (Dyrelius 1985, Skilbrei 1988c). The velocity analysis may be uncertain and leaves additional ambiguity in the interpretation of the depth to the Moho. Together, this makes such calculations as referred to above uncertain. The precision of the two isostatic models are more uncertain, and they neglect the fact that there are variations in the depth to the Moho along the profile. The calculated regional curves were all asymmetric and did not fit any 'usable' regional field (see Fig. 4, p. 213 in Smithson et al. 1974). The form of the calculated should therefore not be used to argue for a strong downward trend in the regional field beneath the JNC.

To avoid using a residual anomaly of maximum amplitude I have chosen a regional field which is somewhat flatter in character; i.e. its downwarping under the Jotunheimen is less pronounced (about 10 mGal different from the regional field used by Smithson et al.). The new gravity model is shown in Fig. 6. Dips of geological contacts at the surface and information from aeromagnetic interpretation has been used when modelling the body geometry.

AEROMAGNETIC INTERPRETATIONS

The aeromagnetic data was acquired as a part of 'The Norwegian Geotraverse Project' (Aalstad et al. 1977). The survey was conducted in 1970 by NGU using a constant altitude of 3400 m above sea level and 3 km profile-spacing which gives an unambiguous coverage, with the line spacing less than twice the altitude throughout the area. The effects of the varying terrain is minimized and the major and deeper features are enhanced relatively to the effects of shallower features.

A complex magnetic anomaly pattern covers the interior of the JNC (Fig. 3). Note the correspondence between the magnetic and the gravity maps. Attention should be paid especially to the magnetic low along the Sjodalen, and to the isolines which parallels the contacts between the JNC and the surrounding gneisses and metasediments. Note also the curvilinear pronounced gradient associated with the Lærdal-Gjende and the Utladalen faults. The Lærdal-Gjende fault must divide the Jotun Complex into two separate areas in order to explain the northward increase of the magnetic anomaly across the fault: the nappe is thin and flat-lying to the south of the fault and the thickness must increase markedly to the north of the fault.

Aalstad et al. (1977) interpreted the JNC to be on average three kilometres thick, i.e. considerably less than the earlier gravity interpretations. We should note that the interpretation was based entirely on spectral analysis, and that the precision of the thickness estimate is much less than the depth estimate (depth to the top of the body).

The magnetic gradient associated with the Lærdal-Gjende Fault continues along the lake Gjende and further to the northeast of it. I propose the fault zone to continue along and to the east of the Lake Gjende. It might continue even further into the Trondheimsfeltet area. Due to less pronounced magnetic features here, this is speculative.

The magnetic map is more complex than the gravity map, and the anomalies do not occur in exactly the same place as the gravity anomaly. This offset can be explained by strong remanent magnetization or that the magnetic and gravity anomalies may be due to different sources. The last possibility is ruled out because of the overall matches between the gravity and magnetic maps. The small offset is due to the fact that magnetite distribution is much more variable than the density variation. This is supported by the magnetic susceptibility data. Fig. 5a and Fig. 5b show percentage histogram and summary statistics of susceptibility for JNC rocks and gneisses; respectively. The mean value of the magnetite bearing JNC rocks (class C in Fig. 5a) shows that the JNC rocks must explain the aeromagnetic anomalies. The surrounding gneisses show low to moderate magnetization. The measurements of magnetic properties on 9 gabbro samples from the Jotun massif, gave low Q-values and thereby possibility 1 above is unlikely. It can therefore be concluded that the offset of the magnetic and gravity anomalies is best explained by the properties of each of the potential fields, rather than by unusual geological models. The varying topography in the area explains much of the complexity in the magnetic field. The pods of high magnetic and high density ultramafic rocks which often occur near mountain peaks (Lutro & Tveten 1989) give rise to the strongest aeromagnetic anomalies.

DISCUSSION

A regional-residual gravity separation is always questionable and subjective. Even authomatic methods that are based on filtering or other techniques are subjective in the sense that parameters must be chosen. Such techniques distort both amplitude and shape of anomalies. In other areas of Scandinavia, where geological data and density data is available to evaluate and check properties of residual maps, the manual subjective methods gave the 'best' residual maps both for qualitative and quantitative interpretations of broad regional to smaller scale structures (Skilbrei 1988b, Elming 1988). The 'objective' methods are hampered by the fact that they do not take into account petrophysical and geological information (although in some cases this can be preferable). The choice of regional trend in the gravity field of the region in earlier studies cannot therefore be considered as the final solution.

It must be remembered that the models could be changed somewhat. The gravity effect is not particularly sensitive to changes in the deeper parts of models, and in addition, no gravity interpretation is unique (Dobrin 1960); an infinite number of models can be made to fit any anomaly. Therefore, combined interpretations based on several data sets are necessary. This study has shown that earlier work has used a residual gravity high of maximum amplitude and a minimum density contrast.

The modelling has also been based on the following observations: (1) The gravity and magnetic fields correspond closely to the outcropping lithologies, (2) The contacts dip inwards. An associated dense body at depth (perhaps of the 'Slidre type') is ruled out by (1). These assumptions are all reasonably well proved to be correct by published geological data and the new density data. The Lærdal-Gjende Fault is strikingly pronounced in the data, implying its tectonic significance. The continuation of the Lærdal-Gjende fault to the east of Gudbrandsdalen is in any case speculative.

A dense body, akin to that causing the Slidre anomaly (Smithson, 1964b), could of course be situated completely within the Precambrian basement underneath the JNC and contribute to the residual anomaly covering the area. Such a situation would be highly accidental, but cannot be disproved. However, it is far more hypothetical than the conclusion of this work which is based on combined geological and geophysical observations and interpretations.

The approximately 6 km thick complex, which is situated in a high position in the nappe units, was probably originally part of a much wider complex that has been transported for a great distance. The similarity of the Jotunheimen and Bergen-Arc high-grade metaplutonic rocks, and many Jotun Nappe rocks matched in the basement to the northwest of Jotunheimen (personal communications E. Tveten 1988) supports this inference. However, lithological similarity alone cannot indicate nappe transport.

SOME REGIONAL TECTONIC IMPLICATIONS

The geophysical interpretation supports the idea that the Lærdal-Gjende Fault is a major dislocation, and that the segments on the northern and southern side of the fault are made up of gently dipping and flat-lying units that were continuous before faulting. The interpretations agree well with the hypothesis that the JNC has been thrust from the northwest and emplaced onto the margin of the Baltic shield (Milnes and Koestler 1985). According to this model, the JNC is presently preserved as an erosional remnant of a much larger nappe complex in a depression or graben structure. The idea of the JNC as an 'Ivrea type' flake with a local root possibly as deep as 16 km which has been taken to support the idea of a Jotunheimen Caledonian Suture (Banham et al. 1979) must be abandoned.

A magnetic gradient is located approximately along the Gudbrandsdalen and the Ottadalen (NGU 1989) trending northwesterly into the off-shore continental shelf, running into the trend of the Jan Mayen Fracture zone. Interpretation of Landsat images show a major lineament (Lindh 1980) along this magnetic lineament. From the new geochemical maps covering Norway, it can be seen that this line is marked by gradients in the contoured maps for element contents of flood sediment samples (R.T. Ottesen, personal communication, 1986). If this 'line' markes a zone separating the basement into a southwestern and a northeastern block, it may represent an old 'in-situ' suture zone which parallels the Protogine zone. Location of earthquakes apparently line up along this northwest running trend demonstrating that this could be a zone of weakness favouring reactivation during tectonic events such as neotectonics. It might indicate that the Jan Mayen Fracture zone is a continuation of a continental structure.

The pre-erosional upper crust mass excess represented by the formerly greater JNC may have caused gravitational instability and regional isostatic adjustments involving vertical tectonics and reactivation of thrusts as normal faults. The gravitationally induced subsidence provided the mechanism to preserve the thickest part of the Jotun complex in a depression or half-graben limited by the Lærdal-Gjende fault to the southeast and the Utladalen fault to the northwest. A half-graben structure which is post-Caledonian in nature may also explain why the Faltungsgraben is preserved in its present position.

The post-orogenic adjustments within the upper lithosphere could have been associated with extensional fault activity. The model involving a dense body at depth of the 'Slidre anomaly type', beneath the Jotunheimen, is abandoned. A Caledonian suture zone trending from the continental shelf outside Hardangerfjorden through Jotunheimen and the central areas of the Trøndelag part of the Faltungsgraben, is not favoured by the new gravity model, but cannot be ruled out. Post-Caledonian continental rifting, transform faulting or flexure of the lithosphere may be plausible models to explain why Caledonian rocks are preserved in a narrow zone almost continuously along such a great length from the off-shore areas outside Hardangerfjorden to the inner Trøndelag area.

CONCLUSION

A close correlation between recent geological mapping, and aeromagnetic, gravimetric and petrophysical data is demonstrated. The combined interpretations provides constraints on the number of possible gravity models which then lead to a new gravity model that suggests the absence of a deep root zone beneath the Jotun Nappe Complex (JNC). The JNC is less than 6 km thick at the most, and the thickness is interpreted to change abruptly across the Lærdal-Gjende fault which is clearly expressed in the potential fields. Previous gravity models are thus unrealistic. They were based on regional-residual gravimetry separation that gave maximum amplitude of the separated anomaly, and minimum value of the density contrast applied. This combined to give results in conflict with aeromagnetic interpretations and recent structural evidences.

The Lærdal-Gjende fault continuous further to the east than previously recognized, and it penetrates at least to the base of the JNC. The gravity model agree with the theory of nappe emplacement, and that faulting along the Lærdal-Gjende fault postdated the thrusting.

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FIGURE CAPTIONS

Fig. 1: Location of the Jotun Nappe Complex and map area in southern Norway.

Fig. 2: Gravity map of the Jotunheimen area. Contour interval is 5 mGal. Jotun Nappe rocks are indicated by the dotted area. Inner frame area correspond to the aeromagnetic map shown in Fig. 3. Gravity profile along A-A'. There is a close correlation between the aeromagnetic anomalies and the gravity anomalies in area and outline. Modified from Smithson et al. (1974) and Sigmond et al. (1983).

Fig. 3: Aeromagnetic total field map of the Jotunheimen area. All magnetic lows are marked by L and hatched areas. H denote magnetic high. Note the magnetic low zone along the Sjodalen and the pronounced curvilinear gradient trending from Lærdal northeasterly to the northeast of the lake Gjende.

Fig. 4a: Percentage histogram and summary statistics of density for Norite. No ultrabasics included. Class width 100 SI. The median is significantly lower in value than the arithmetic mean.

Fig. 4b: Percentage histogram and summary statistics of density for granitic, quarts-monzonitic and micaceous gneiss; north and west of Jotun nappe. Class with 100 SI. Only representative rock samples were measured. Note that the spread is small, thus the arithmetic mean is close to the median value.

Fig. 5: Percentage histogram and summary statistics of magnetic susceptibility for gneiss (Fig. 5a) and Norite (Fig. 5b). Class width is 0.2 decade. Susceptibility in SI; class A,B,C denote total sample, low-magnetic fraction and high-magnetic fraction, respectively.

Fig. 6: Gravity model along profile A-A' shown in Fig. 2. Observed gravity values correspond to gravity stations established at triangulation points by NGO (1977). The accuracy of triangulation points +/-0.2 m (Midtsundstad & Bakkelid 1977). For the Bouguer correction and the terrain correction, a value of 2670 kg/m^3 was used. The error which this introduces in the final gravity model is small since the variable density has been accounted for by modelling also from

the sea surface to the terrain surface. The small area to the southeast of the nappe where residual values are weakly negative are believed to represent granite. If these values are defined to be positive, or zero, the model will be insignificantly deeper.

Fig. 1

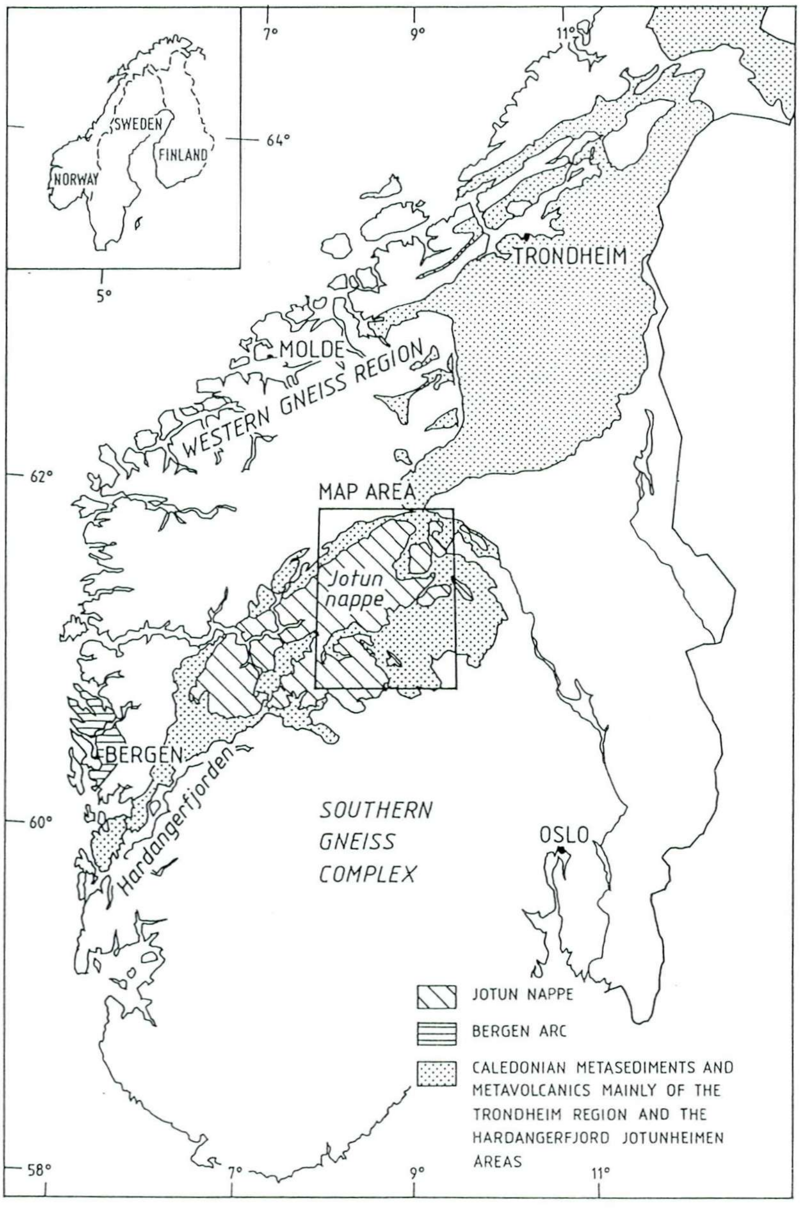

SWEDEN
FINLAND
NORWAY
64°
5°
7°
9°
11°
TRONDHEIM
MOLDE
WESTERN GNEISS REGION
62°
MAP AREA
Jotun nappe
BERGEN
Hardangerfjorden
60°
SOUTHERN GNEISS COMPLEX
OSLO
JOTUN NAPPE
BERGEN ARC
CALEDONIAN METASEDIMENTS AND METAVOLCANICS MAINLY OF THE TRONDHEIM REGION AND THE HARDANGERFJORD JOTUNHEIMEN AREAS
58°
7°
9°
11°

Fig. 2

GRAVITY MAP

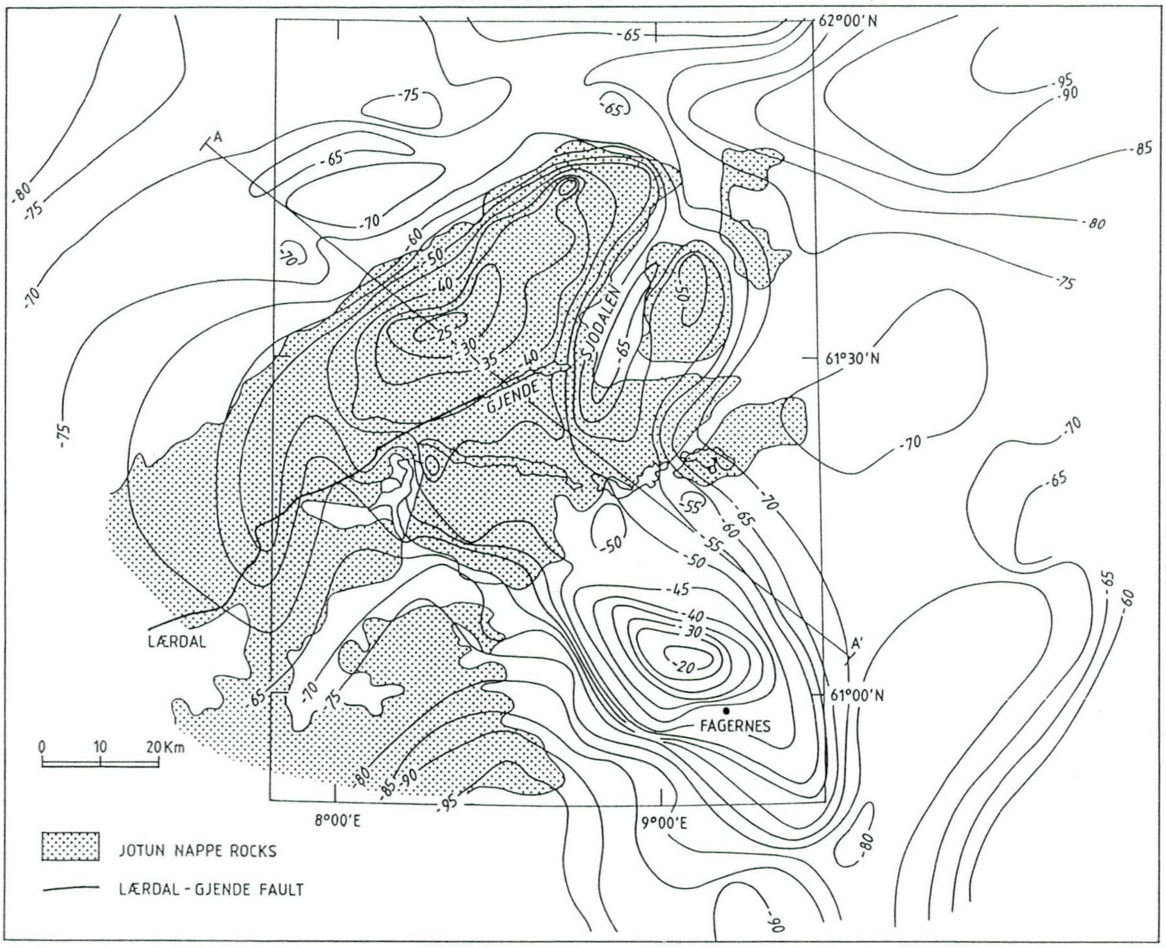


Fig. 3

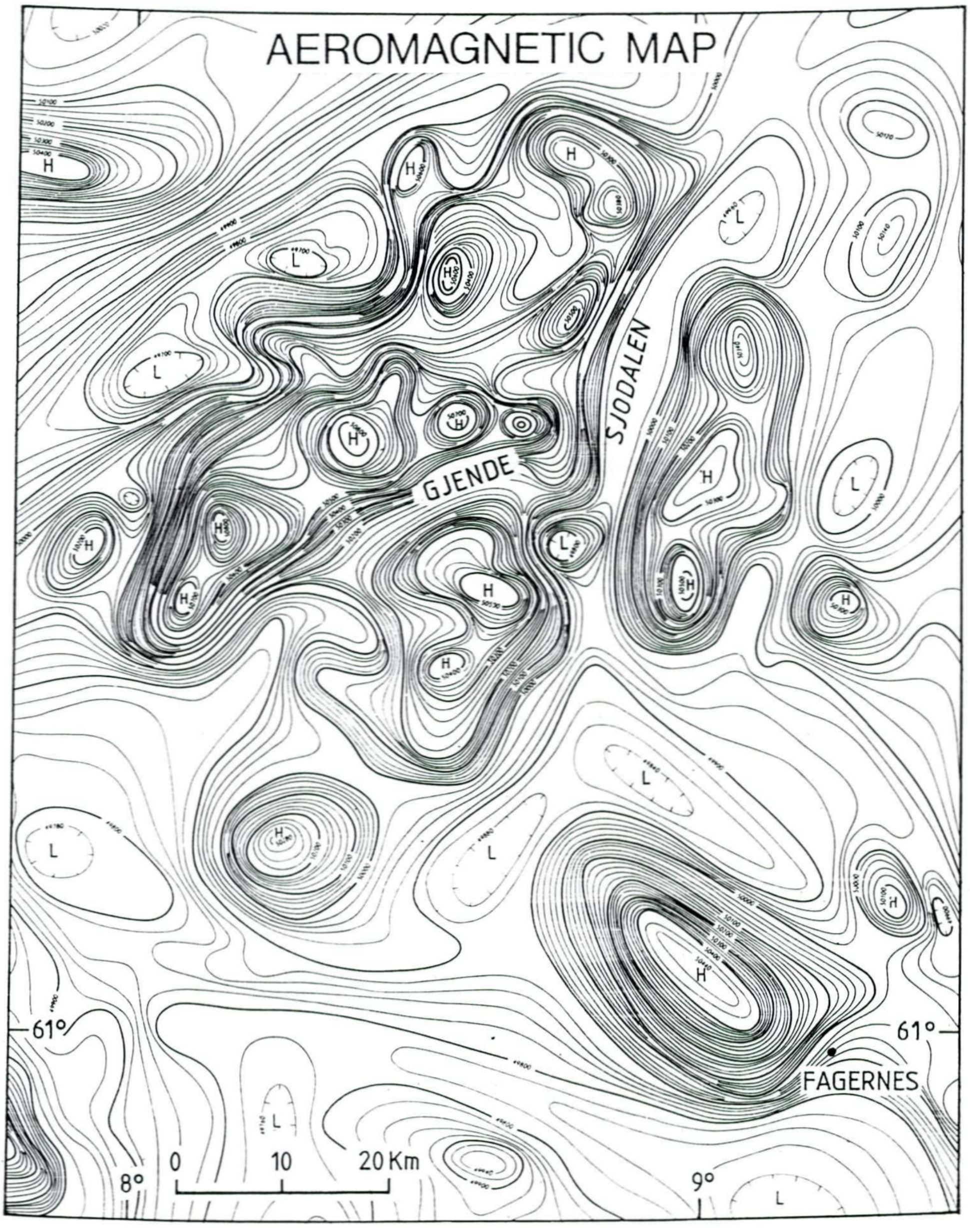

AEROMAGNETIC MAP
SJODALEN
GJENDE
FAGERNES
61°
61°
8°
9°
0
10
20 Km
H
L

Fig. 4

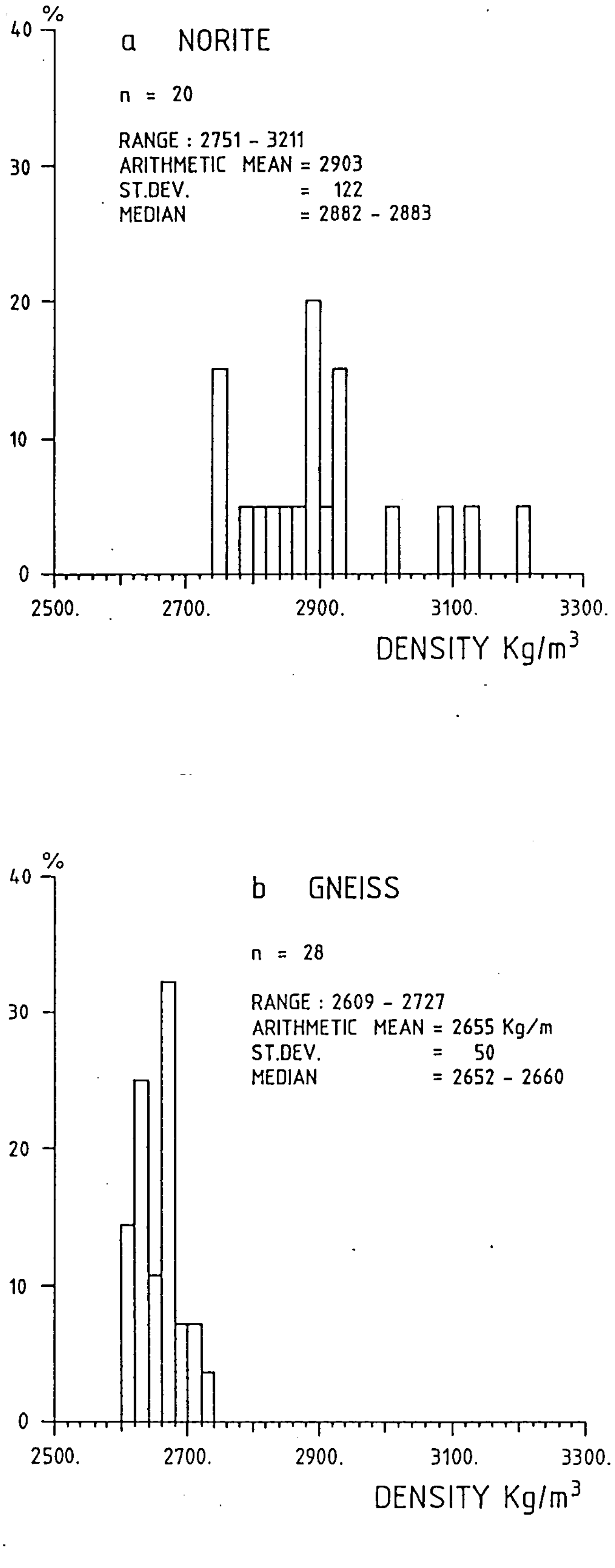
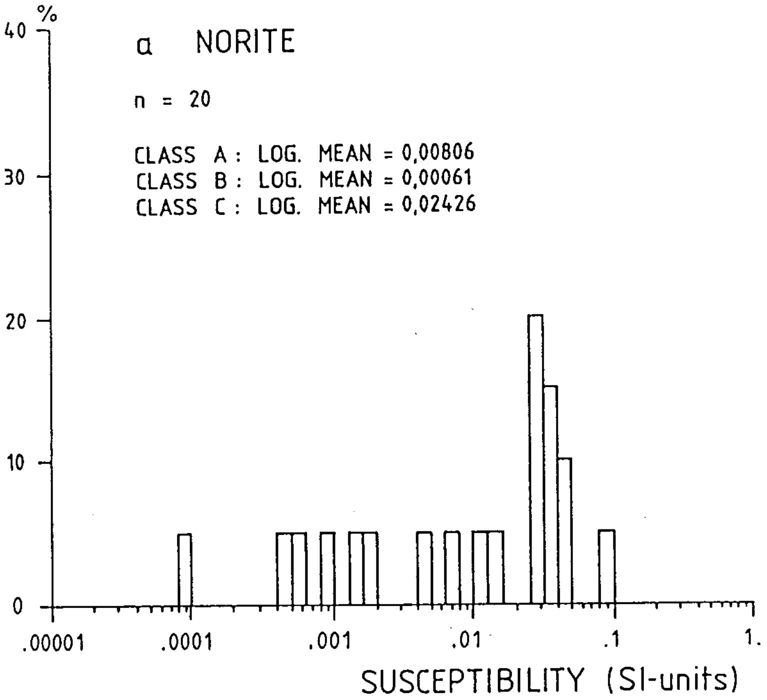
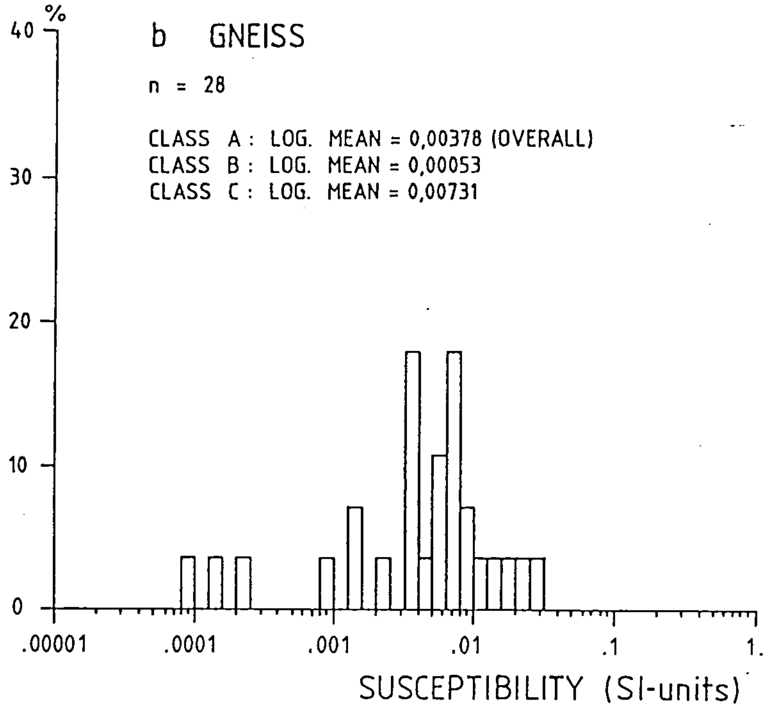

%
40
30
20
10
0
a NORITE
n = 20
RANGE : 2751 - 3211
ARITHMETIC MEAN = 2903
ST.DEV. = 122
MEDIAN = 2882 - 2883
2500.
2700.
2900.
3100.
3300.
DENSITY Kg/m3
%
40
30
20
10
0
b GNEISS
n = 28
RANGE : 2609 - 2727
ARITHMETIC MEAN = 2655 Kg/m
ST.DEV. = 50
MEDIAN = 2652 - 2660
2500.
2700.
2900.
3100.
3300.
DENSITY Kg/m3

Fig. 5

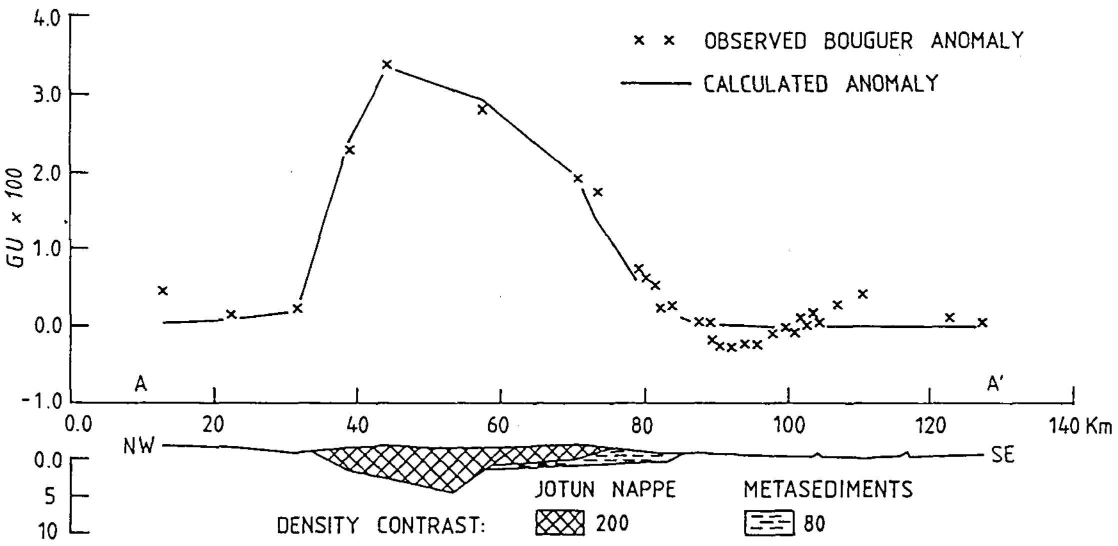


%
40
30
20
10
0
a NORITE
n = 20
CLASS A : LOG. MEAN = 0,00806
CLASS B : LOG. MEAN = 0,00061
CLASS C : LOG. MEAN = 0,02426
.00001
.0001
.001
.01
.1
1.
SUSCEPTIBILITY (SI-units)



%
40
30
20
10
0
b GNEISS
n = 28
CLASS A : LOG. MEAN = 0,00378 (OVERALL)
CLASS B : LOG. MEAN = 0,00053
CLASS C : LOG. MEAN = 0,00731
.00001
.0001
.001
.01
.1
1.
SUSCEPTIBILITY (SI-units)

Fig. 6


4.0
3.0
2.0
1.0
0.0
-1.0
GU × 100
× × OBSERVED BOUGUER ANOMALY
CALCULATED ANOMALY
A
A'
0.0
20
40
60
80
100
120
140 Km
NW
SE
0.0
5
10
JOTUN NAPPE
METASEDIMENTS
DENSITY CONTRAST:
200
80