Geological correlation of magnetic susceptibility and profiles from Nordre Strømfjord, southern West Greenland

Bo M. Nielsen and Thorkild M. Rasmussen

The Palaeoproterozoic Nagssugtoqidian orogen is dominated by reworked Archaean gneisses with minor Palaeoproterozoic intrusive and supracrustal rocks. The Nagssugtoqidian orogen (Fig. 1) was the focus of regional geological investigations by the Geological Survey of Denmark and Greenland (GEUS) in 2001 (van Gool *et al.* 2002, this volume). In conjunction with this project, geophysical studies in the inner part of Nordre Strømfjord, Kuup Akua and Ussuit were undertaken as part of the Survey's mineral resource assessment programme in central West Greenland. The studies include geophysical modelling of airborne magnetic data, follow-up studies of aeromagnetic anomalies by magnetic ground surveying, and geostatistical treatment and integration of different geological, geophysical and geochemical data. The aim is to obtain an interpretation of the region in terms of both regional geological features and modelling of local features of relevance for the mineral resource assessment. This paper presents an account of the field work and some of the new data.

The work was carried out from a rubber dinghy in the fjords and from helicopter-supported inland camps. *In situ* measurements of the magnetic susceptibility of rocks and magnetic ground profiles were carried out during a period of 25 days in June and July 2001. In total 133 localities were visited from three camps.

The data collected will be used together with magnetic properties and density of rock samples determined in the laboratory for geophysical modelling of the area. The petrophysical data will constrain the geophysical and geological interpretations and thus provide a higher degree of confidence in the models.

Magnetic susceptibility

Magnetisation is defined as the magnetic moment per unit volume. The total magnetisation of a rock is the vector sum of the remanent magnetic moment that exists irrespective of any ambient external magnetic field, and the induced magnetic moment that exists because of the presence of the external magnetic field. The strength and direction of the induced magnetic moment is proportional to the strength and direction of the external magnetic field. The proportionality factor is termed the magnetic susceptibility (denoted with the symbol χ and assumed to be a scalar quantity). In the following sections all quantities are referred to the SI system (Système International) in which the magnetic susceptibility becomes dimensionless.

The magnetic susceptibility of rocks was measured with a hand-held magnetic susceptibility meter (Fig. 2). To obtain estimates of the remanent magnetic component and more precise results of the magnetic susceptibility it is also necessary to investigate rock samples in the laboratory. The *in situ* measurements presented in this paper were obtained during the field work; the results of laboratory investigations currently being carried out at the petrophysical laboratory at the Geological Survey of Finland are not yet available.

The amount and distribution of the magnetic minerals in a rock determine the magnetic response measured along a profile. The content of magnetite (Fe_3O_4) and its solid solution ulvöspinel (Fe_2TiO_4) is the dominating factor in crustal rocks (Blakely & Connard 1989). The magnetic susceptibility of gneiss is normally between 0.1×10^{-3} SI and 25×10^{-3} SI (Telford *et al.* 1998).

Data acquisition and processing

The magnetic susceptibility meter used in the field was a Geo Instrument GMS-2 (Fig. 2). Depending on the homogeneity of the rocks and the size of the outcrop, ten to forty readings were taken at each locality to ensure a proper statistical treatment of the measurements. Outcrops were selected so as to provide the most representative measurements of the rock on unweathered, smooth surfaces. In total 3444 readings were taken at the 133 localities. In the statistical treat-

Geology of Greenland Survey Bulletin 191, 48–56 (2002)

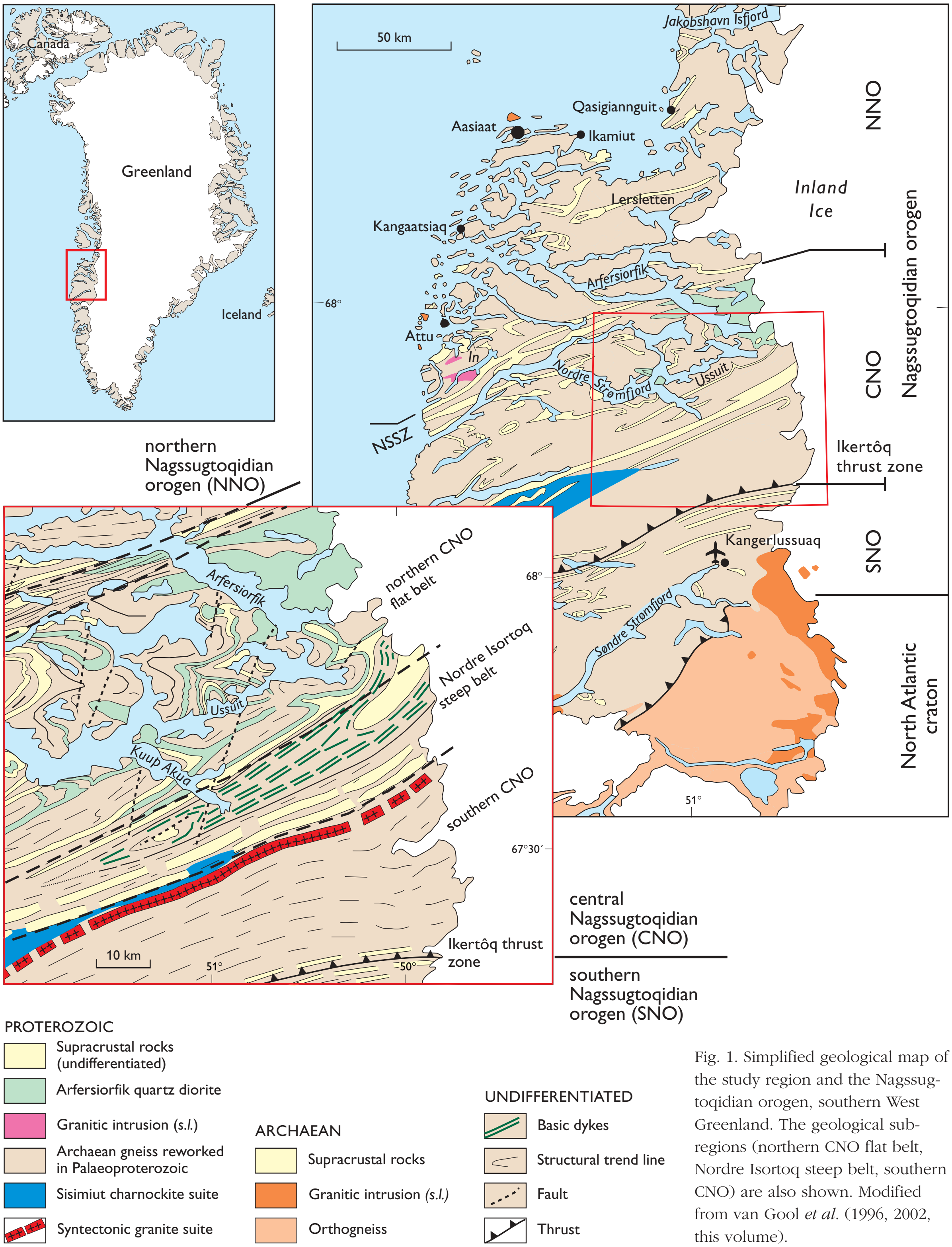

Fig. 1. Simplified geological map of the study region and the Nagssugtoqidian orogen, southern West Greenland. The geological subregions (northern CNO flat belt, Nordre Isortoq steep belt, southern CNO) are also shown. Modified from van Gool *et al.* (1996, 2002, this volume).
NSSZ: Nordre Strømfjord shear zone; **In**: Inuarullikkat.

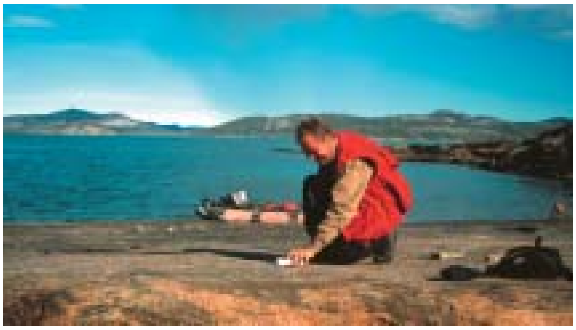

Fig. 2. The hand-held magnetic susceptibility meter is small and easy to use. Measurements are taken first with the meter at the rock surface, followed by a reference reading with the meter held up in the air. The photograph shows the first step of the measurements on typical gneiss lithologies in the central part of Ussuit fjord.

ment the measurements were grouped according to locality, rock type and geological province. In cases of very heterogeneous rocks, the relative proportions of the rock types present were estimated and data weighted accordingly. Magnetic susceptibility measurements were also made as a secondary task by two other field teams in the western part of Nordre Strømfjord, at Attu, in the Ikamiut area and at Lersletten, but these data are not included in this presentation.

Two long magnetic profiles were made (Fig. 3) with measurements of both the total field and the vertical gradient using a magnetic gradiometer (Geometrics G-858); another magnetometer (Geometrics 856) was used as base magnetometer. The sampling distance along the profiles was approximately 1 m. As an example, the magnetic total field intensity from the south-

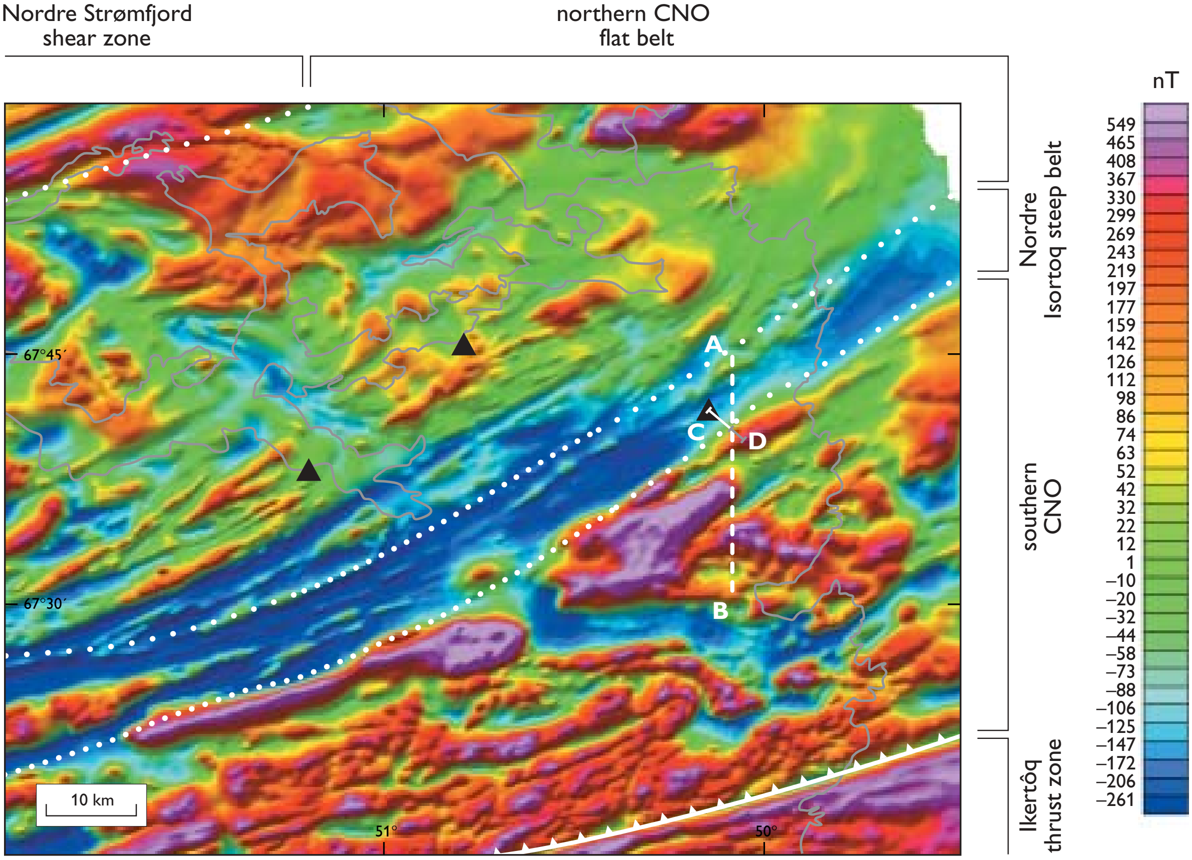

Fig. 3. Magnetic total-field intensity map with shaded relief. The tectonic boundaries and subregions of the central Nagssugtoqidian orogen stand out as distinct lineaments and zones in the magnetics. Shading is with illumination from the north-north-west. **Black triangles** mark the position of the three field camps in the study area. **Dotted lines** mark the boundaries within the central Nagssugtoqidian orogen. **Closely spaced dots** indicate boundaries mapped in the field, and **wider-spaced dots** extrapolations based on the aeromagnetic data. The airborne and ground magnetic profiles are shown with **dashed** (A–B) and **full white lines** (C–D), respectively. The part of the ground profile used for modelling is shown as the **grey part** of the line C to D (see also Fig. 5).

ernmost two kilometres of the profile undertaken from the eastern inland camp south of Ussuit is discussed in a later section.

Regional geology

Reworked Archaean gneisses with minor Palaeoproterozoic supracrustal and intrusive rocks dominate the Nagssugtoqidian orogen. The region studied in this paper lies in the eastern part of the central Nagssugtoqidian orogen (CNO; Marker *et al.* 1995). The CNO is bounded by the Nordre Strømfjord shear zone to the north and the Ikertôq thrust zone to the south (Fig. 1).

The CNO can be divided into three *subregions*: (1) the northern CNO flat belt; (2) the Nordre Isortoq steep belt; and (3) the southern CNO (van Gool *et al.* 1996; Connelly & Mengel 2000).

Subregion 1. The rocks of the northern CNO flat belt are dominated by Archaean orthogneisses with a grey to white colour and variably developed banding; major open upright antiformal structures are characteristic. The gneisses are intercalated with narrow belts of Palaeoproterozoic supracrustal rocks, spatially associated with the calc-alkaline Arfersiorfik intrusive suite. The supracrustal rocks are often strongly foliated and migmatised with several leucosome phases, and comprise mafic amphibolite bodies and layers, ultramafic bodies, pelitic schists, marble and calc-silicate rocks, and fine- to medium-grained quartz-rich paragneisses with biotite and garnet.

Subregion 2. The Nordre Isortoq steep belt separates the northern CNO flat belt and the southern CNO. The steep belt is a zone of steeply dipping and isoclinally folded orthogneiss and paragneiss, and is dominated by an up to five kilometres wide belt of supracrustal rocks. The supracrustal rocks comprise mainly pelitic and psammitic paragneisses, with lesser amounts of mafic to ultramafic bodies and layers, amphibolites and calc-silicate rocks. The gneisses are very variable in appearance, and range from felsic migmatitic gneiss types to more pelitic and mafic types. The rocks are in granulite facies.

Subregion 3. The southern CNO consists dominantly of homogenous orthogneisses.

The study region is cross-cut by several NE–SW-trending faults of unknown age. The rocks to the west of Kuup Akua and north of the northern border of the Nordre Isortoq steep belt, including the Ussuit area, are all in amphibolite facies. The rocks to the east of Kuup Akua and further north are in granulite facies.

Regional aeromagnetic data

The aeromagnetic anomaly data for the study region resulting from project *Aeromag 1999* (Rasmussen & van Gool 2000) were obtained by subtraction of the International Geomagnetic Reference Field (IGRF) from the measured data, and correlate well with the surface geology of the region (Figs 1, 3).

The subdivision of the CNO and the boundary features are clearly reflected in the aeromagnetic anomaly data. The Nordre Strømfjord shear zone stands out as a sharp discontinuous ENE–WSW lineament. Magnetic domains can also be recognised coinciding with the three geological subregions.

Subregion 1. The northern CNO flat belt is characterised by elongated and curved, short wavelength anomalies reflecting the folded nature of this domain. These anomalies are superimposed on a regional magnetic field level of around zero.

Subregion 2. The Nordre Isortoq steep belt stands out as an ENE–WSW-trending regional magnetic low with superimposed low amplitude, elongated, short wavelength anomalies. Based on the magnetic data alone, it may be argued that the northern border of the steep belt should be placed more northerly than that depicted in Fig. 3, for which only the central part has so far been confirmed by mapping. The low magnetic anomaly is partly due to the presence of supracrustal rocks. Uniform low magnetic response of supracrustal rocks is confirmed from many other regions of the world (Card & Poulsen 1998).

Subregion 3. The southern CNO has a high magnetic regional level and is characterised by closely spaced short wavelength anomalies with steep horizontal gradients. Several fold structures can be recognised in the magnetic anomaly patterns. A NNW–SSE-trending low magnetic feature cross-cuts the eastern part of the southern CNO. The anomaly is weak in the steep and flat belt regions.

The border between the CNO and the southern Nagssugtoqidian orogen (SNO; Fig. 1; van Gool *et al.* 2002, this volume) stands out as a very sharp and large gradient, which can be correlated with the Ikertôq thrust zone.

Magnetic susceptibilities of different rock types

The magnetic susceptibility measurements presented here show that the different rock types exhibit a wide range of susceptibility values within the same formation, and even on the same outcrop. The measurements for the main rock types of the studied area are given in Fig. 4 and Table 1.

The susceptibility in SI units for the entire data set ranges from 0.0 to 91.41 × 10^{-3} SI. The rock types examined include orthogneisses, paragneisses, a variety of supracrustal rocks, and intrusives related to the Arfersiorfik quartz diorite. The highest values correspond to orthogneisses, whereas some marbles and gneisses are virtually non-magnetic.

Gneiss

The susceptibility distribution for all types of gneisses is shown in Fig. 4A. In total, 2372 measurements were made on 77 gneiss localities. The variability of the gneisses in the field is reflected in very variable magnetic susceptibilities ranging from 0.0 to 68.18 × 10^{-3} SI, with a geometric mean value of about 1.21 × 10^{-3} SI. The negative skewness (Table 1) of the measurements in Fig. 4A shows an asymmetric tail extending towards lower values. This may reflect that the generally low measured susceptibility values have a too low mean, perhaps due to near-surface weathering of the rocks.

In general, the metamorphic facies is reflected in the susceptibility values, with high values for granulite facies gneisses and lower values for amphibolite facies gneisses. This is probably caused by the formation of magnetite under granulite facies metamorphism (Clark 1997). Moreover, the gneiss type is clearly reflected in the susceptibility values, with low values for paragneisses and higher values for orthogneisses. Visible magnetite was often observed in migmatites, which possibly indicates formation of magnetite during migmatisation, and is reflected in the high susceptibility values.

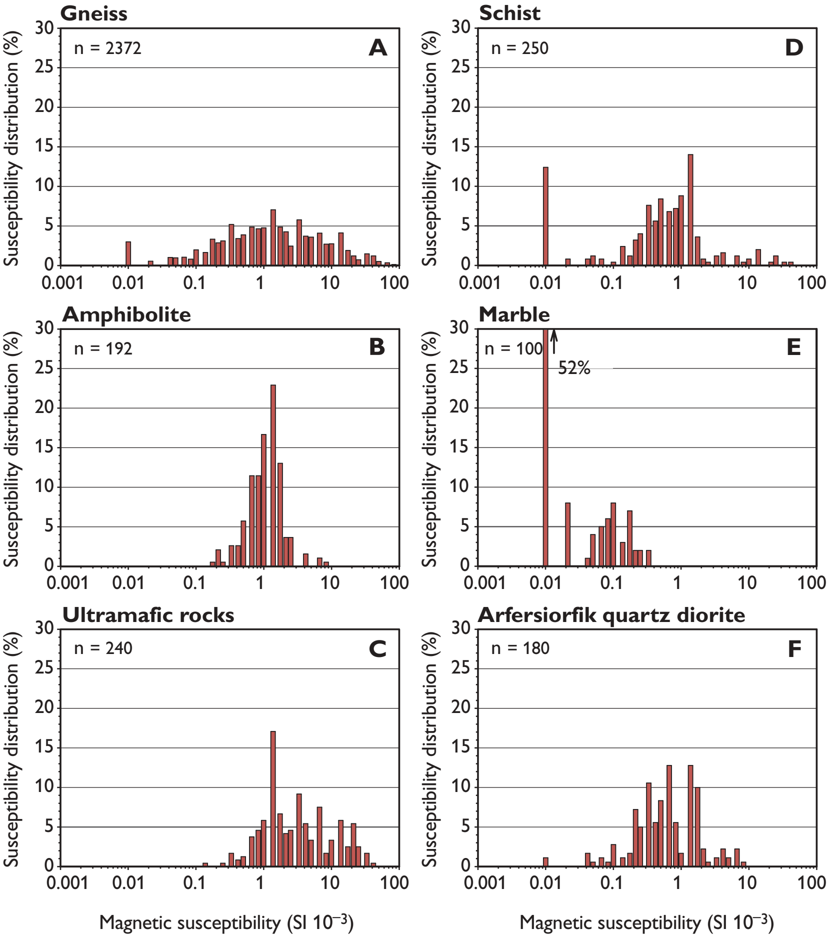

Fig. 4. Magnetic susceptibility distribution in per cent for different rock types.

Table 1. Measurements of magnetic susceptibility

Rock type	Number of measurements	Minimum SI x 10^{-3}	Maximum SI x 10^{-3}	Geometric mean SI x 10^{-3}	Skewness
Gneiss	2372	0.00	68.18	1.21	–0.12
Amphibolite	192	0.17	7.33	0.94	–0.02
Ultramafic rocks	240	1.00	19.44	2.75	1.92
Schist	250	0.00	34.70	0.59	0.21
Marble	100	0.00	0.30	0.05	–0.29
Arfersiorfik quartz diorite	180	0.69	6.88	0.53	–0.45

The skewness characterises the degree of asymmetry of a distribution around its mean. The geometric mean is the mean of all the obtained susceptibility values larger than zero for the given rock type.

Amphibolite

Measurements of magnetic susceptibility of mafic amphibolite (Fig. 4B) were taken at eight localities, and give a susceptibility range from 0.17 × 10^{-3} SI to 7.33 × 10^{-3} SI. The amphibolites are characterised by fairly uniform distribution of the values with a geometric mean of 0.94 × 10^{-3} SI. These susceptibility values are typical for amphibolite, reflecting their mafic, paramagnetic mineralogy (Henkel 1991; Clark 1997). The highest values were obtained from amphibolites within gneiss lithologies, and the lowest values from amphibolites in supracrustal sequences.

Ultramafic rocks

The susceptibility distribution for ultramafic rocks is shown in Fig. 4C. Compared to the mafic amphibolites, the ultramafics have higher susceptibility values ranging from 1.0 to 19.44 × 10^{-3} SI for seven localities. The high values reflect the high iron content of the ultramafic rocks. Despite the high skewness (Table 1), the high values are in accordance with general values for ultramafic rocks (Clark 1997). Some of the highest values were obtained on magnetite-rich reaction rims along contacts with the neighbouring rocks. The ultramafic rocks are often heavily altered, which can explain some of the lower susceptibility values obtained.

Schist

The susceptibility values for mica schists range from 0.0 to 34.7 × 10^{-3} SI (Fig. 4D) taken at eight localities. Susceptibility values obtained for pelitic schists were higher than for more psammitic schist types; higher iron content of the pelitic schists in an oxidising environment favours metamorphic formation of magnetite. It should be noted, however, that both pelitic and psammitic schists at several localities had a large content of graphite. The carbon from the graphite can

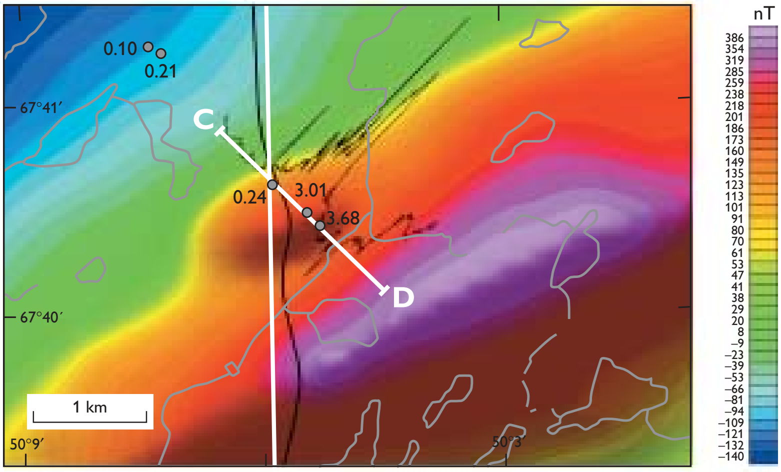

Fig. 5. Magnetic total-field intensity map with shaded relief. The response observed from the airborne and ground magnetic survey profiles south of Ussuit (see Fig. 1). The NNW–SSE-trending **white line** C–D shows the location of the ground profile. The N–S-trending **white line** is the airborne magnetic profile. The white lines also define the zero level for the magnetic total field intensity data shown as a **black curve**. The **grey circles** show locations where selected susceptibility values were obtained in the field.

have a reducing effect, which hinders the formation of magnetite. As was the case for the amphibolites, the negative tail of the distribution possibly reflects weathered rocks.

Marble

Marbles from five localities are very similar, all with very low susceptibility values (Fig. 4E) due to the high content of non-magnetic calc-silicate minerals. The highest values for marble were obtained at one locality where the marble contained thin intercalated mafic mica schist bands and was penetrated by pegmatite veins. In general, the magnetic susceptibility is almost negligible, and the marble lithologies can thus be considered as forming non-magnetic units.

Intrusive rocks: Arfersiorfik quartz diorite

Susceptibility values were taken at six outcrops of the Arfersiorfik quartz diorite, and fall into two groups (Fig. 4F). The first group has high values ranging from 0.69 to 6.88 × 10^{-3} SI, while the second group has lower values between 0.01 and 1.10 × 10^{-3} SI. Field observations indicate that the quartz diorite varies in appearance from dark to light coloured types, due to varying amounts of mafic components, quartz content and grain size, which may explain the variance of the susceptibility values.

Magnetic profile data

The NNW–SSE profile measured from the eastern inland camp south of Ussuit is perpendicular to the southern border of the Nordre Isortoq steep belt (line C to D in Figs 3, 5). The profile runs from the low magnetic zone of the steep belt into a more irregular high magnetic anomaly zone. The profile was laid out as a straight line, with start and end points together with every 100 m interval determined by use of the Global Positioning System (GPS).

The central part of this ground profile crosses a small positive anomaly. One of the aims was to compare the details obtained from the ground measurements with a profile from the *Aeromag 1999* survey (Rasmussen & van Gool 2000). The airborne magnetic profile was flown at an altitude of 300 m, runs N–S and intersects the ground profile (Fig. 5). The difference in content of short wavelength anomalies in the two survey types (Fig. 5) clearly illustrates the attenuation with increased distance to the sources, which has significant implications for the amount of detail that can be acquired from the airborne data. However, a clear correlation with the observed surface geology is confirmed by the ground profile.

The sharp positive anomalies observed in the central part of the ground profile correlate with a 100–150 m wide zone containing ultramafic rocks, whereas the lower magnetic anomalies reflect gneiss lithologies. The locations of the lowest anomalies can be related to calc-silicate horizons observed in the field. Based on these observations it can be concluded that the small positive anomaly in the aeromagnetic data originates from the presence of ultramafic rocks.

Combined forward modelling and inversion undertaken with tabular bodies as the principal model is shown in Fig. 6 for both the ground and airborne profile. The free parameters in the final inversion are location, size, thickness and magnetic properties. Some initial modelling with the dip angle as free parameter indicates that a steep northward dip of the bodies gave the best data-fit. In the final inversion the dip angles for all bodies were identical, except one body for which it was necessary to deviate slightly from the common angle in order to obtain a proper data-fit. The relatively thin alternating bodies of rocks with different magnetic properties, necessary in the modelling, reflect the banded nature of the geology in the study region.

To test the agreement of the field susceptibility measurements with the values obtained by the modelling, the modelling was undertaken without any constraints on the magnetic properties, but with the assumption that the direction of magnetisation was aligned along the present direction of the geomagnetic field. Thus the modelling does not distinguish between a remanent magnetisation in the direction of the geomagnetic field and the induced magnetic component. The magnetic susceptibility values for the bodies in the modelling range from 0 to 92 x 10^{-3}, with a mean around 30 x 10^{-3}. This is one order of magnitude higher than the geometric mean values of the measured susceptibility values, but within the range obtained from the measured values. An explanation to this discrepancy may be that the remanent magnetic component contributes considerably to magnetisation; however, this has not been confirmed by laboratory measurements on rock sample from the Survey's archive.

Although modelling of potential field data is known to be highly ambiguous, the model presented above includes features that are expected to be common to all

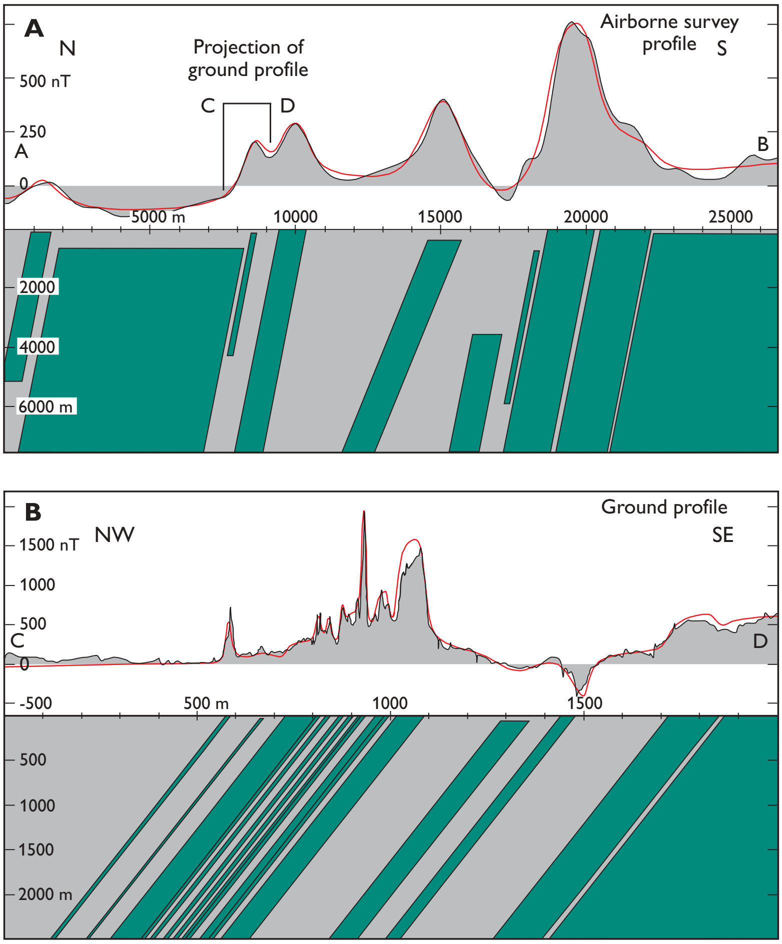

Fig. 6. **A**: The airborne profile data (A–B, the dashed white line in Fig. 3) and the resulting model from the modelling with the projection of the ground profile (line C–D in Figs 3, 5). **B**: The ground profile data and the resulting model from the modelling. Measured magnetic total field intensity data are shown in **black**, and the response of the models in **red**. **Green-coloured bodies** are the magnetic bodies used to model the measured data. The grey shaded regions in the model correspond to magnetic reference level; i.e. zero magnetic susceptibility.

models that are realistic representations of the geology. More detailed modelling and further study including measurements of the magnetic properties are warranted.

Conclusions and further work

The aeromagnetic data reflect the regional geology well. Further work will involve interpretation through processing and modelling.

The ongoing construction of a large database of magnetic susceptibilities and other petrophysical parameters, coupled with observations on rock types and structures, will help to elucidate the correlation between the geology and magnetic responses, and is a prerequisite for realistic geological interpretations of the aeromagnetic surveys from the area.

The field measurements show that the magnetic susceptibility is variable within the same rock type, and even on individual outcrops there are considerable variations. Gneiss and schist lithologies in particular have very variable susceptibilities, probably reflecting the variable nature of the lithologies, e.g. pelitic to psammitic. Ultramafic rocks and amphibolites, and to a lesser extent some intrusives of the Arfersiorfik quartz diorite suite, show relatively high magnetic susceptibilities within a narrow range. Marble is essentially a non-magnetic rock type. All susceptibility values obtained from the different lithologies are within the typical range for such rock types (Clark & Emerson 1991; Shive *et al.* 1992; Clark 1997; Telford *et al.* 1998), and are in agreement with values obtained in previous investigations (Thorning 1986). The variable susceptibility values of the rock types reflect the different nature of the rocks and their different geological histories, e.g. metamorphism, hydrothermal alteration, bulk composition, etc. More work will be necessary to analyse the susceptibility values in relation to these factors. The discrepancy between the susceptibility values obtained in the field and those indicated by modelling will also have to be investigated further. The ground magnetic profile carried out during the field season illustrates well the significant difference in resolution of the geological details that are possible from different survey types, at the same time confirming the correlation of geology and airborne anomalies.

The investigations will continue in the 2002 field season, when ground geophysical surveys will be undertaken in connection with lineament studies and the study of a mineralised horizon in amphibolite at the fjord Inuarullikkat (Stendal *et al.* 2002, this volume). The database of the magnetic susceptibility of rocks will be supplemented with new measurements and with laboratory determinations of petrophysical properties when these become available.

Acknowledgements

Jette Blomsterberg and Aaju Simonsen (both Bureau of Minerals and Petroleum, Government of Greenland) are thanked for their contributions to the field work. The project is part of a Ph.D. study by B.M.N. at the University of Aarhus and is funded by GEUS and the Danish Research Agency. The Geological Institute of the University of Copenhagen is thanked for lending us the magnetic gradiometer.

References

Blakely, R.J. & Connard, G.G. 1989: Crustal studies using magnetic data. In: Mooney, W.D. (ed.): Geophysical framework of the continental United States. Geological Society of America Memoir **172**, 45–60.

Card, K.D. & Poulsen, K.H. 1998: Geology and mineral deposits of the Superior Province of the Canadian Shield. In: Lucas, S. (ed.): Geology of the Precambrian Superior and Grenville Provinces and Precambrian fossils in North America. Geology of Canada **7**, 13–194. Ottawa: Geological Survey of Canada (also The geology of North America **C-1**, Geological Society of America).

Clark, D.A. 1997: Magnetic petrophysics and magnetic petrology: aids to geological interpretation of magnetic surveys. AGSO Journal of Australian Geology and Geophysics **17**(2), 83–103.

Clark, D.A. & Emerson, D.W. 1991: Notes on rock magnetization characteristics in applied geophysical studies. Exploration Geophysics **22**, 547–555.

Connelly, J.N. & Mengel, F.C. 2000: Evolution of Archaean components in the Paleoproterozoic Nagssugtoqidian orogen, West Greenland. Geological Society of America Bulletin **112**(5), 747–763.

Henkel, H. 1991: Petrophysical properties (density and magnetization) of rocks from the northern part of the Baltic Shield. Tectonophysics **192**, 1–19.

Marker, M., Mengel, F.[C.] & van Gool, J.[A.M.] 1995: Evolution of the Palaeoproterozoic Nagssugtoqidian orogen: DLC investigations in West Greenland. Rapport Grønlands Geologiske Undersøgelse **165**, 100–105.

Rasmussen, T.M. & van Gool, J.[A.M.] 2000: Aeromagnetic survey in southern West Greenland: project *Aeromag 1999*. Geology of Greenland Survey Bulletin **186**, 73–77.

Shive, P.N., Blackely, R.J., Frost, B.R. & Fountain, D.M. 1992: Magnetic properties of the lower continental crust. In: Kay, R.W. (ed.): Continental crust. Developments in geotectonics **23**, 145–177.

Stendal, H., Blomsterberg, J., Jensen, S.M., Lind, M., Madsen, H.B., Nielsen, B.M., Thorning, L. & Østergaard, C. 2002: The mineral resource potential of the Nordre Strømfjord – Qasigiannguit region, southern and central West Greenland. Geology of Greenland Survey Bulletin **191**, 39–47 (this volume).

Telford, W.M., Geldart, L.P. & Sheriff, R.E. 1998: Applied geophysics, 2nd edition, 770 pp. Cambridge: Cambridge University Press.

Thorning, L. 1986: A decade of geophysical surveying in Greenland. Rapport Grønlands Geologiske Undersøgelse **128**, 123–133.

van Gool, J.[A.M.], Marker, M., Mengel, F.[C.] & field party1996: The Palaeoproterozoic Nagssugtoqidian orogen in West Greenland: current status of work by the Danish Lithosphere Centre. Bulletin Grønlands Geologiske Undersøgelse **172**, 88–94.

van Gool, J.A.M. *et al.* 2002: Precambrian geology of the northern Nagssugtoqidian orogen, West Greenland: mapping in the Kangaatsiaq area. Geology of Greenland Survey Bulletin **191**, 13–23 (this volume).

Authors' address

Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark. E-mail: *bmn@geus.dk*