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KURT-ÅKE MAGNUSSON

A PETROPHYSICAL AND PALAEOMAGNETIC STUDY OF THE NORDINGRÅ REGION IN EASTERN SWEDEN

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ABSTRACT

A petrophysical and palaeomagnetic study has been carried out in the Nordingrå region of eastern Ångermanland, central Sweden. The sub-Jotnian gabbro-anorthosite complex and the Jotnian sandstones, as well as the post-Jotnian Ulvö dolerite sheet, have been investigated. It appears that the thermal effect of the large dolerite sheet has caused an extensive remagnetization of the adjoining gabbro-anorthosite complex and therefore reset the remanent magnetization into a direction which is similar to that of the Ulvö dolerite (anorthosite: D=47.5°, I=–32.1° and Ulvö dolerite: D=47.5°, I=–45.1°). The direction of remanent magnetization of the Jotnian sandstone is also similar to that of the Ulvö dolerite (D=48.8°, I=–39.1°).

The *in-situ* susceptibility measurements across the gabbro-anorthosite massif show low and uniform susceptibility values throughout the whole gabbro complex, while the anorthosite is characterized by having two separate areas of contrasting susceptibilities. The gabbro and the anorthosite, situated at the western margin of the anorthosite outcrop, are characterized by low susceptibility values of paramagnetic magnitude, that is, the magnetization is mainly carried by the paramagnetic minerals. The eastern part of the anorthosite outcrop has about 10 times higher susceptibility than the western margin. This is due to a higher magnetite content in the eastern area.

The multiple intrusion character of the Ulvö dolerite sheet is evident by the chemistry of the components as well as by the different susceptibility patterns of the units. The sheet is characterized by a lower unit with low and uniform susceptibility values and an upper unit with higher and more varying susceptibility values.

The variation and average values of the density and magnetic properties (intensity and direction of remanent magnetization as well as susceptibility) of the investigated rocks have been established by measurements on collected specimens.

The magnetic minerals responsible for the observed magnetic properties of these rocks have been identified by Curie temperature measurements and by using reflectance and scanning electron microscopy. Microscopy of the magnetic minerals has also helped to clarify the observed correlation between susceptibility and Q-ratio (that is, the trends in the plot of specimen susceptibility *versus* Q-ratio).

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INTRODUCTION

The Geology Department, Chalmers University of Technology/University of Göteborg, has a research programme in progress within the Nordingrå region (Fig. 1). S.-Å. Larson (1980) has presented a Doctor's Thesis on the Ulvö dolerite, and G. Lundqvist (1976) has presented an unpublished thesis on the gabbro-anorthosite complex in Nordingrå. A study of quicksand structures in the Jotnian sandstones of the Nordingrå region has been presented by Bergman (1980) who is presently involved with an extensive study of these sandstones.

This present study, which concerns the petrophysical properties of the rocks in the Nordingrå area (the Ulvö dolerite, the sub-Jotnian gabbro-anorthosite complex and the Jotnian sandstone), forms a part of this research programme. The availability of extensive geological data about these rocks simplifies the interpretation of measured petrophysical properties. The object of this investigation is to use the available geological information to achieve a better understanding of the petrophysical properties.

The density and magnetic properties (susceptibility as well as intensity and direction of the remanent magnetization) were measured on collected hand specimens. All samples were hammer cut and the orientation of the samples measured with a magnetic compass or a solar compass. The samples were demagnetized by treatment in alternating magnetic fields with different peak field intensity. The object of the demagnetization was to examine the character of the remanent magnetization and to establish the palaeomagnetic pole position of these rocks.

In-situ susceptibility measurements have been carried out across the gabbro-anorthosite complex (Figs. 1 and 3) and across the dolerite sheet at 9 different sites (Figs. 1 and 3). The purpose of these measurements across the dolerite sheet was to investigate whether the chemically established multiple intrusion character of the Ulvö dolerite at three sites (Lundqvist & Samuelsson 1973; Larson 1980) could also be detected along other sections through the Ulvö dolerite. The *in-situ* measurements across the gabbro-anorthosite complex were carried out in order to discover if any differences in the magnetization occurred across this massif.

The minerals which are responsible for the measured magnetic properties were studied by reflected light microscopy and scanning electron microscopy.

GEOLOGICAL SETTING

The Nordingrå region and the adjacent area are characterized by contrasting topography comprising narrow valleys and inlets which accentuate the block-type structure of the bedrock; the inlets often continue inland as valleys. This region has a high rate of post-glacial uplift of approximately 8 mm a year, and also the

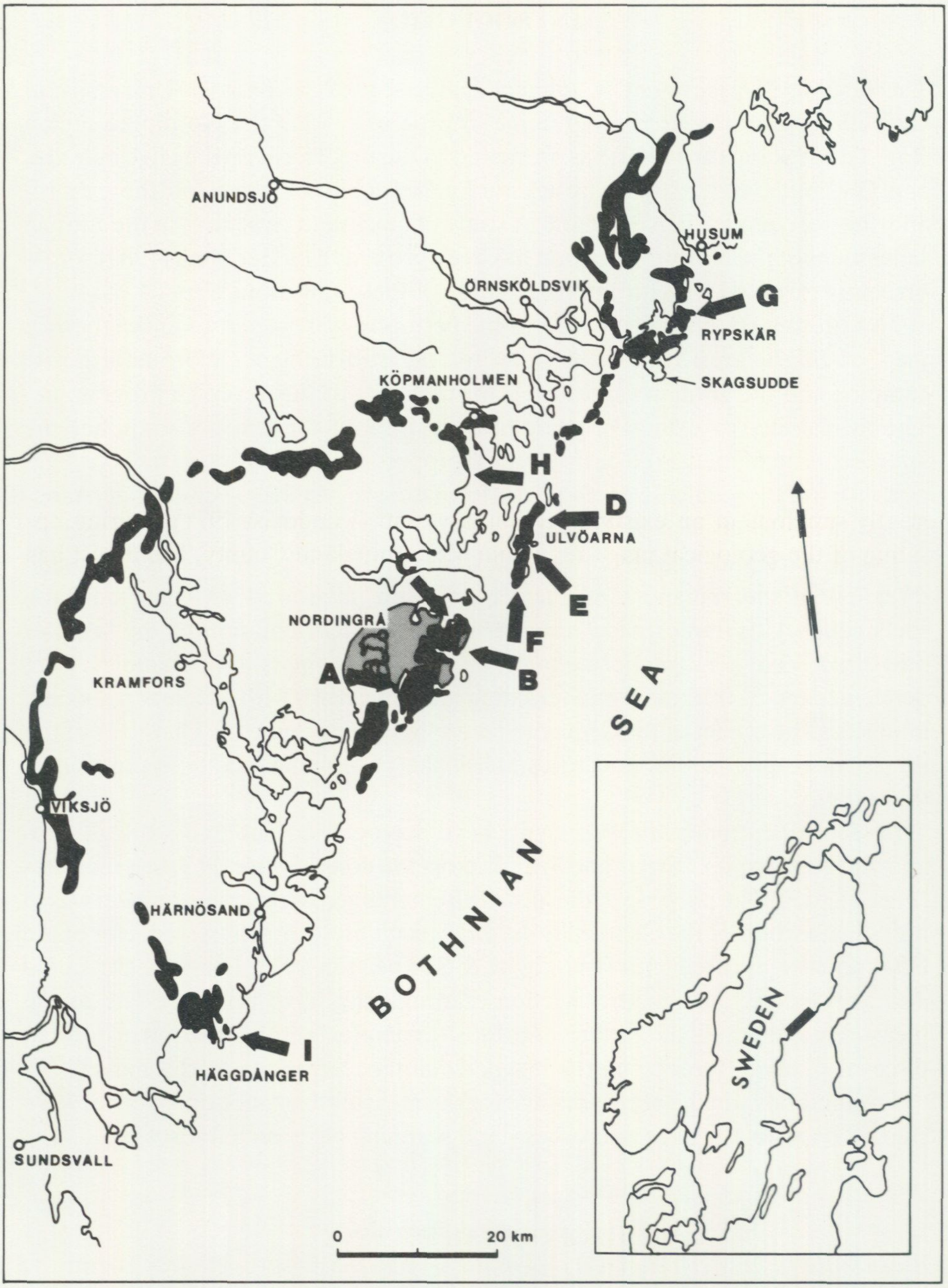

Fig. 1. Map showing the location of the investigated area. Black is dolerite. Grey shows the position of the investigated area of the gabbro-anorthosite massif and the Jotnian sandstone. Arrows show the position of the investigated dolerite sites: Ringkallen (A), Edsätterfjärden (B), Rävsön (C), Norrsand (D), Ulvösundet (E), S. Ulvön (F), Rypskär (G), Köpmanholmen (H), and Häggdånger (I). (Modified from Lundqvist & Samuelsson 1973.)

highest observed ancient shore-line at 285 m above the Bothnian sea (Hörnsten 1964). The Bothnian coast is one of two areas in Sweden which are characterized by a relatively high frequency of earthquakes (Magnusson *et al.* 1963; Båth 1978) and it is therefore likely that block movements have periodically taken place along the observed morphological lineaments. Faults of considerable vertical throw, up to about 200 m, have been established along some of the marked lineaments (Larson & Magnusson 1979; Larson 1980). However, no major block rotation has occurred between the Ulvö dolerite province which includes Nordingrå, and the Satakunta dolerite province in south-western Finland, since Jotnian time (Magnusson & Larson 1977; Neuvonen 1965).

The area has been previously investigated by Lundbohm (1899) who published a petrographical map of Västernorrland County, and by Sobral (1913), (see Fig. 2); the adjoining Västerbotten County has been mapped by Gavelin (1955). A new petrographical map of Västernorrland County to the scale of 1:200, 000 is in preparation by Thomas Lundqvist (Geological Survey of Sweden) which will greatly supplement an existing preliminary map (Lundqvist 1971). During up-dating of the geological mapping within Västernorrland County, Lundqvist has found that the predominating rock is a metagreywacke which is in part strongly migmatized. The greywackes were intruded by a suite of igneous rocks ranging in composition from ultrabasic to granitic during early phases of the Svecokarelian orogeny (c. 1900 Ma). The area was also intruded by late orogenic granites (cf. Lundqvist 1980; Magnusson *et al.* 1960).

The Nordingrå intrusive complex, consisting of anorthosite, gabbro and granite, were intruded during the anorogenic stage following the Svecokarelian orogeny. Radiometric dating of the Nordingrå granite and gabbro (Welin and Lundqvist, in preparation; see also Lundqvist 1980) gives an age of about 1550 Ma. The gabbro is intruded by the Nordingrå granite.

All these intrusive rocks are overlain by a formation of Jotnian sandstones. Högbom (1909) introduced the term sub-Jotnian for such igneous complexes underlying Jotnian sandstones. *In-situ* arkoses may attain a thickness of 20 m, which below the Jotnian sedimentary rocks define an erosion surface between the sub-Jotnian and the Jotnian. The sandstones have a gentle dip of c. 5–10° to the south-east end an observed maximum thickness of about 60 m (Lundbohm 1899; Sobral 1913).

A younger rock in the Nordingrå area is the post-Jotnian olivine dolerite of alkali basalt type (the Ulvö dolerite), which forms a sill or sheet with an approximate thickness of 250 m (Lundqvist & Samuelsson 1973; Larson & Magnusson 1979). The dolerite dips gently towards the Bothnian sea. However, still younger dolerite dykes mostly steep and narrow with a maximum width of 5 m intrude into the dolerite sheet.

Radiometric dating (K-Ar isochron method) of the Ulvö dolerite gives an age of about 1 245 Ma (Welin & Lundqvist 1975; Welin 1979). The sandstones are found

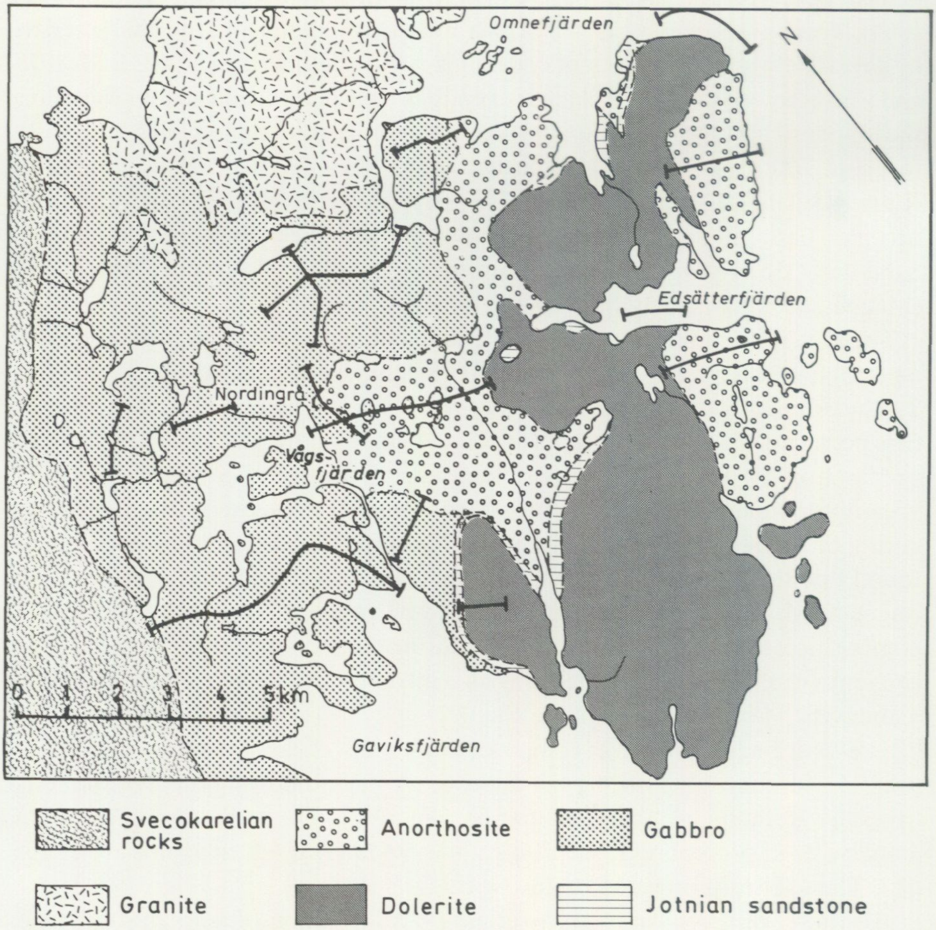

Fig. 2. Petrographical map of the investigated area of the Nordingrå region. ├──┤: measured susceptibility profiles. (Modified from Sobral 1913.)

below the Ulvö dolerite sill because they have been protected by the latter from removal by erosion (see Fig. 2; after Sobral 1913 and Lundqvist & Samuelsson 1973).

GENERAL DESCRIPTION OF THE INVESTIGATED ROCKS

THE GABBRO-ANORTHOSITE MASSIF

The anorthosite, as well as the gabbro, are penetrated by porphyritic and pegmatitic gabbro dykes (Sobral 1913; von Eckermann 1938). Large fragments of anorthosite have been observed in the porphyritic gabbro, although the anorthosite itself has also fragments of (slightly older) anorthosite (von Eckermann 1938; G.Lundqvist 1977). The contact between the anorthosite and the gabbro may be sharp or diffuse and lacks any chilled margin effects. In some places there is a gradual merging of the two rocks into each other; in other cases they are separated either by porphyritic or by pegmatitic rocks (von Eckermann 1938). The FeO: MgO ratio of the silicate matrix in the anorthosite (after elimination of the Fe and Ti which would preferentially enter the ore components) is about the same as the FeO: MgO ratio in the gabbro (von Eckermann 1938). Investigations by von Eckermann (op. cit.) and by G.Lundqvist (1977) have shown that the anorthosite probably originated by differentiation of the same magma as the gabbro. Field and geochemical evidence thus indicate an intimate genetic connection between the gabbro and the anorthosite. Furthermore, the latter probably developed *in-situ* from a gabbro-anorthosite magma. G.Lundqvist (1977) has reported igneous layering and lamination in the gabbro from six locations in the area. The layering is rather flat with a dip varying between 10 and 30 degrees. This, together with the fact that the directions of strike and dip are variable indicates the rather flat internal structure of the gabbro-anorthosite complex. Moreover G.Lundqvist (1977) has found that within this massif there exist no trends in chemical composition relating to topographical height or geographical location.

The main minerals comprising the gabbro (after Sobral 1913; von Eckermann 1938) are as follows.

Diamagnetic minerals: plagioclase which often is zonal (ranging in composition from labradorite cores to andesine margins). Minor diamagnetic minerals, such as apatite, quartz, orthoclase, and zircon, are also often present.

Paramagnetic minerals: Pyroxene (whereupon orthorhombic and monoclinic modifications are present in about equal amounts), olivine and subordinate biotite, amphibole and serpentine.

The ortho- and clinopyroxenes and olivine are rather rich in iron with about 60%–70% FeO in the pyroxenes and with 68%–86% fayalite in solid solution with forsterite (von Eckermann 1938 and G. Lundqvist 1977).

The anorthosite consists of about 70%–95% plagioclase (An 50-An 70) together with pyroxene, olivine, opaque minerals, apatite, biotite, orthoclase, and quartz as primary constituents, and oxide phases, amphibole, chlorite and serpentine as secondary constituents (Sobral 1913). Von Eckermann (1938) has included also prehnite and epidote. The main diamagnetic and paramagnetic minerals are plagioclase, orthoclase, quartz and olivine, pyroxene, amphibole, biotite, chlorite, serpentine, respectively.

ULVÖ DOLERITE

The dolerite is characterized by rhythmic igneous layering, further supported by the modal variation of femic and salic minerals (Larson 1973). Especially within the distinctly rhythmically layered parts of the dolerite, igneous lamination has frequently been developed. This is caused by the prefered orientation of tabular plagioclase, in part also of prismatic augite crystals, subparallel with the plane of layering (Lundqvist & Samuelsson 1973; Larson 1980). The thickness of the different layers generally varies between one centimetre and one metre. Discordant, graded layering and slumping structures have been noted by Lundqvist & Samuelsson (1973) and Larson (1980). Chilled margins have been observed at different localities and these margins have an alkali olivine basaltic composition (Larson 1980). The rock is usually medium-grained but irregular bodies and thin veins of very coarse-grained dolerite (dolerite pegmatite) frequently occur although these constitute only a minor part of the dolerite intrusion (Larson 1980). The main minerals of the Ulvö dolerite are plagioclase, augite, olivine, biotite, and Fe-Ti oxides; accessories are apatite, potash feldspar, sericite, serpentine, amphibole, epidote, and quartz (Lundqvist & Samuelsson 1973; Larson 1980). In places the dolerite sheet is characterized by layers enriched in Fe-Ti oxides; these titaniferrous iron ore horizons have been mined at several places on the Ulvö Islands. The magnetization in the Ulvö dolerite is completely governed by the ferromagnetic Fe-Ti oxides.

A chemical and petrological investigation by Lundqvist & Samuelsson (1973) on the dolerite at Ringkallen shows an intrusion which is multiple in character; two main units have been distinguished and each unit occupies about half of the total thickness of the sill. The lower unit is more uniform in texture, chemistry and modal composition than the upper. Rhythmic layering is only present in the upper unit, where there is an increase in plagioclase and augite and a decrease in olivine contents towards the upper margin. The whole-rock analyses also show an upward increase in the content of SiO_2, TiO_2, $Fe_2 O_3$, Na_2O, K_2O, P, and CaO and a decrease in FeO, MgO, Cr, Ni: Co and the Niggli mg value. The upper unit also shows trends relating to the chemical composition of the minerals, for example, the forsterite content of olivine and the anorthite content of plagioclase (often normally zoned) decreases upwards (Fo: 60%–24% and An: 70%–40%). The fractionation was affected mainly by crystal settling from the magma, which is evident by the lamination of plagioclase and augite in the upper part of the layered unit (Lundqvist & Samuelsson 1973). It is also evident that Fe-Ti phases are involved in the settling process (Larson & Magnusson 1976).

Analysis of the chemical composition across the dolerite sheet has also been carried out at Norrsand (northern Ulvön) and Rypskär by Larson (1980). The chemical investigation at northern Ulvön resulted in a division of the sheet into four zones comprising: lower zone (Lz), rhythmically layered zones (Rza and

Rzb) and upper zone (Uz). (See Figs.44 and 67, pp. 74 and 124 in Larson 1980). The approximately 30 m thick Lz zone is rather uniform in chemical and modal composition and generally lacks layering. The rhythmically layered Rz zones (c. 150 m thick) consist of an olivine and magnetite enriched Rza zone and a pyroxene and plagioclase enriched Rzb zone. The Uz zone (c. 70 m thick) shows no layering, i.e, no cumulus minerals. The fayalite content of olivine as well as the ferrosilite content of orthopyroxene increases from lower Rza zone to upper Rzb zone. The Lz zone is characterized by a relatively low iron content in the mafic minerals.

Certain trace elements (Cu, Co, Cr, U, and Ni), especially Cr and Ni, show an increase from lower Lz, have a maximum at the upper Lz, and thereafter decrease. The above mentioned data of Larson (1980) indicate a multiple intrusion. Larson has suggested that the lower, more uniform zone (Lz), represents an initial magma surge and the other zones (Rz and Uz) represent a later, intimately related magma surge. The Rz zones show a similar chemical pattern as the upper at Ringkallen. The Lz zone is much thinner compared to the lower uniform unit at Ringkallen. The Lz zone also has a somewhat different chemical character than the lower Ringkallen unit; the latter is probably contaminated by the wall rock (Lundqvist & Samuelsson 1973; Larson 1980).

The layering at Rypskär is not as evident as at northern Ulvön. However, the trends in mineral chemistry across the sheet, for example, the forsterite content of olivine, show a sudden break at a level approximating to about half the height of the sheet. This indicates a multiple intrusion. The upper half of the sheet shows a more strongly layered character with a higher content of mafic minerals, especially augite and Fe-Ti oxides. The upper unit has also a higher fayalite content in the olivine and lower content of anorthite in plagioclase as well as lower enstatite content in pyroxene. Respectively, these two units at Rypskär correspond rather well to the upper and lower unit at Ringkallen.

JOTNIAN SANDSTONE

The Jotnian sandstone formation in the Nordingrå region is characterized by a variety of sandstones, shales and conglomerates which are normally underlain by a layer of "*in-situ*" material (regolith), derived partly from Svecokarelian rocks and partly from the sub-Jotnian complex (Bergman 1980). Conglomerate, consisting principally of quartz pebbles but also of granite and gneiss pebbles cemented together by quartzitic sandstone, has been found resting directly on arkose (regolith), (Sobral 1913 and Bergman 1980). It should be noted, however, that the sandstone is also associated with intraformational conglomerates and intercalations of shale (Lundqvist & Samuelsson 1973; Bergman 1980).

The sandstones dip at about 5–6 degrees to the south-east and have an observed maximum thickness of approximately 60 m (Sobral 1913; Bergman 1980). They consist principally of quartz and cloudy feldspar fragments; accessory minerals include mica, opaque minerals and kaolinite (Sobral 1913). Due to the small amounts of disseminated hematite, the sandstones are light red in colour (Bergman 1980). According to Sobral (1913), the sandstone has an insignificant proportion of cementing material. When present, it consists mostly of ferruginous material which may be hematite or of an argillaceous nature. The feldspar present is mostly a perthitic orthoclase; the dominating mica mineral is muscovite together with rare amounts of biotite. Accumulations of kaolinite and muscovite are also found (Sobral 1913). The sandstones thus consist mainly of diamagnetic minerals. Hematite occurs as rounded particles and as lamellar crystals or in clusters of very minute grains. Magnetite occurs very sparsely as inclusions in orthoclase and as more independent grains (Sobral 1913).

SAMPLING AND MEASUREMENTS

The susceptibility meter used for the *in-situ* measurements was developed by the Geological Survey of Finland and modified by the Geophysical Division of the Geological Survey of Sweden (SGU). It measures a volume of rock equal to a hemisphere of about 30 cm in radius.

Susceptibility measurements across the dolerite sheet (from lower to upper margin) were carried out at the Ulvö Islands, Nordingrå, Häggdånger, Köpmanholmen, and Rypskär (Fig. 1). The sheet is 200–250 m thick and the measurements were made at about 4 m intervals. These measurements were carried out along two profiles (Köpmanholmen and Häggdånger) across a large ring-shaped lopolithic intrusion outcropping between Köpmanholmen and Åvikebukten (Lundqvist & Samuelsson 1973; see Fig. 1). Three additional profiles were measured at Nordingrå (Fig. 2): Ringkallen, Edsätterfjärden and Rävsön and also along three profiles on the Ulvö Islands: Norrsand (N.Ulvön), Ulvösundet (S.Ulvön) and Skagsudde (S.Ulvön), (see Figs. 1, 3 and 4).

The susceptibility measurements at Rypskär were conducted across a roughly semicircular dolerite body north-east of Örnsköldsvik (Fig. 1). The dolerite intrusion is situated on the shore of the Bothnian sea and only about half of the semicircular body outcrops on land (cf. Figs. 2 and 11 in Larson & Magnusson 1979). The measurements at Norrsand (N.Ulvön) and Rypskär were made in those areas previously investigated by Larson (1980) and at Ringkallen following similar petrochemical works by Lundqvist & Samuelsson (1973).

Susceptibility measurements were also conducted along profiles across the gabbro-anorthosite complex at Nordingrå (Fig. 3). In order to detect possible variations in susceptibility relating to geographical location and topographical height, the measurements were carried out across the hills. As the hill slopes usually also lack an overburden of Quaternary sediments, this allowed a tighter density of measurements. The topographical height of each measurement was

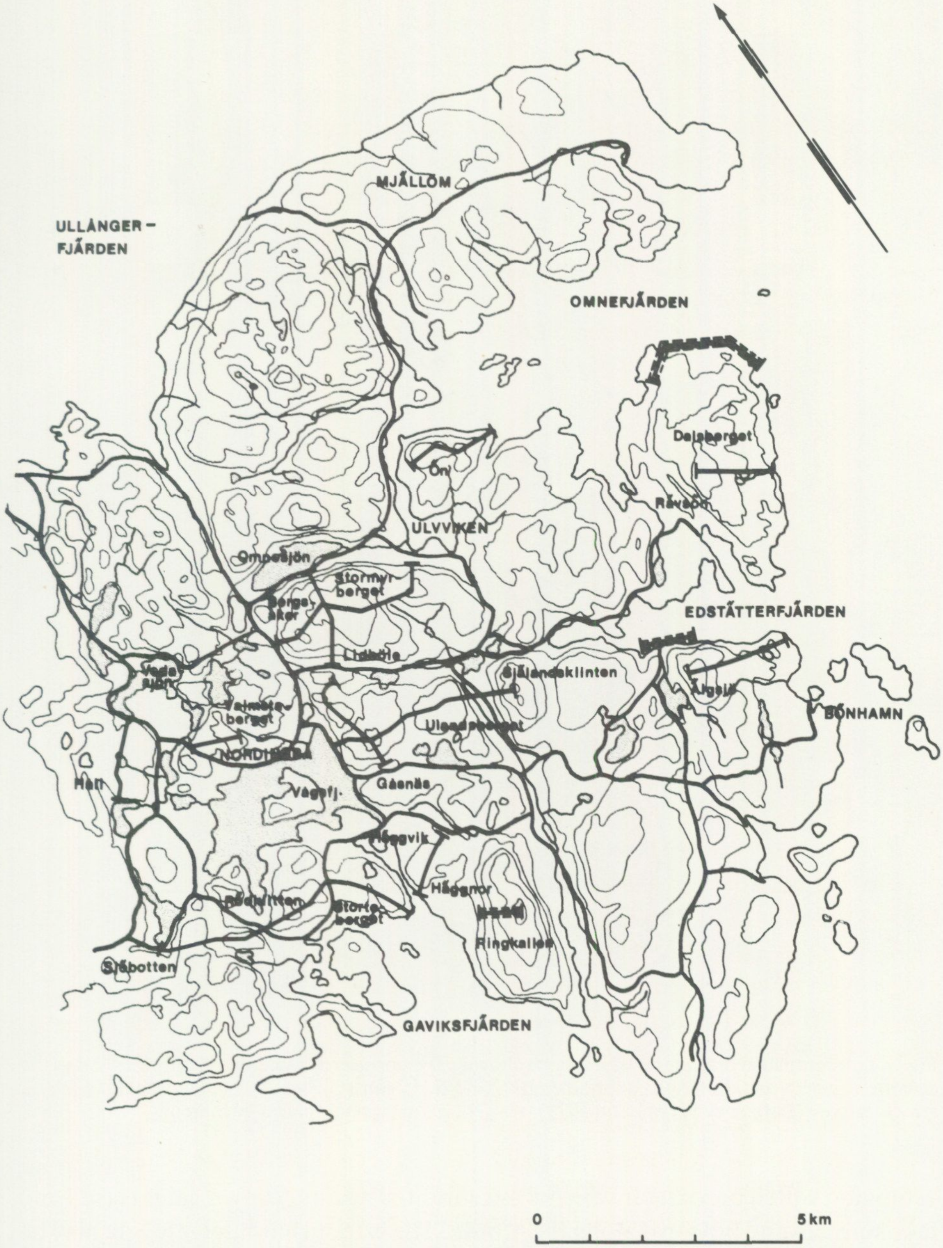

Fig. 3. Topographical map of the investigated area of the Nordingrå region showing the *in-situ* measured susceptibility profiles. Contour inverval of altitude above sea-level is 50 m. ⊢——⊣ : profiles across the gabbro-anorthosite massif. ⊨==⫤ profiles across the Ulvö dolerite sheet.

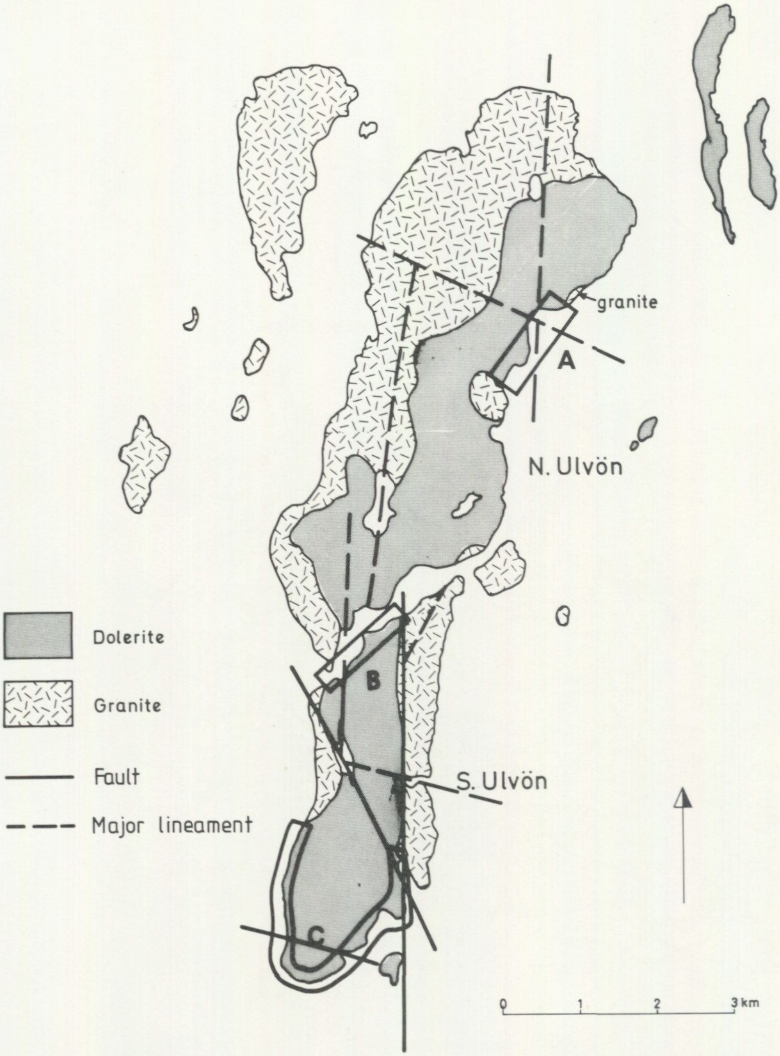

Fig. 4. Petrographical map of the Ulvö region showing the position of susceptibility profiles across the dolerite sheet. Norrsand (A), Ulvösundet (B), and S. Ulvön (C). ⊢—⊣ : faults established by a gravity survey (Larson & Magnusson 1979). ⊢---⊣ : major topographical lineament.

estimated with a barometer which was calibrated against known heights (sea and lake surfaces and hill tops) along the profile. The error in barometer height may be up to 5 m. Because the rough topography of the Nordingrå region (the variation in topographical height is often greater than 200 m), the error in measured barometer height will constitute only a small percentage of the total variation in height along the profiles. A total profile length of 20 km has been measured with about 20 m between the measurements (Fig. 3).

Fig. 5. Topographical map of the investigated area of the Nordingrå region showing the position of the collected samples. Contour interval of altitude above sea-level is 50 m. ●: gabbro, ○: anorthosite, ◉: Jotnian sandstone. Arrows show the position of samples with directions of magnetization unrelated to the dolerite sheet. ⊢---⊣ : major topographical lineament.

The gabbro, anorthosite and sandstone were sampled for subsequent petrophysical and palaeomagnetic investigations (Fig. 5). The petrophysical properties and palaeomagnetic pole position of the dolerite sheet have been presented in earlier works (Larson & Magnusson 1976; Magnusson & Larson 1977). All samples were hammer cut and their orientation measured using a magnetic compass or solar compass. A total of 29 gabbro and 20 anorthosite samples were taken at 17 and 8 different sites, respectively (Fig. 5).

The sandstones, which in some outcrops attain a thickness of about 60 m, where sampled at different stratigraphical levels. Depending on the extent of the outcrops, samples were collected at height intervals ranging from 5 to 10 metres. The sampling was carried out at eight different outcrops in the Nordingrå area (Fig. 5).

Block movements of considerable vertical throw have taken place along faults in the Nordingrå region (Larson & Magnusson 1979). In order to obtain an average value of the palaeopoles, including the influence of the block movements, the sampling was spread over the greater part of the area (Fig. 5).

PETROPHYSICAL PROPERTIES:GENERAL INTRODUCTION

The porosity of igneous rocks is usually very low and will at most influence the density by approximately –0.02 g/cm^3 (Henkel 1976). If sufficient amounts of ore minerals are present, they will cause an increase (due to their high density 4.8–5.2 g/cm^3) of the rock's bulk density. Increased magnetite content increases both the density and induced magnetization (susceptibility) of the rock. Henkel (1976) has quantified this relation which makes it possible to reduce the bulk density to silicate density, i.e. the influence of iron oxide components on the bulk density is removed. He based this empirical relation upon 30 000 specimens of igneous rocks collected from northern Sweden. Apart from the Ulvö dolerite, the rocks investigated in this study (gabbro, anorthosite and sandstone) generally has lower susceptibility values than 10^{-3} cgs units and the iron oxide content will therefore not influence the bulk density.

In the Precambrian magmatic rocks (representing a compositional variation from ultramatic to leucogranitic rocks) of northern Sweden, Henkel (1976) found that the silicate density closely correlates with the mineral composition and thus also with the chemical composition. This is demonstrated for igneous rocks by correlation trends between density and SiO_2 content, and the CM/AF-index (Ca+1.2 Mg)/(K+1.43 Na). Secondary processes influencing the density of the rocks will strongly affect these trends. The density can therefore give an approximate estimate of the composition of the rock.

Rocks are characterized by two types of magnetizations: induced and remanent. The induced magnetization requires the presence of an external magnetic field whilst remanent magnetization does not. Thus, the induced magnetization originates when the rock is influenced by an external field which magnetizes the rock in the direction of the field. In a weak field such as the geomagnetic field, induced magnetization is proportional to the field strength;the constant of proportionality is called susceptibility. The susceptibility of a rock is thus a measure of its ability to acquire a magnetization in the presence of a magnetic field and is dependent on the type and amount of magnetic minerals present in the rocks.

The remanent magnetization is a residual permanent magnetization in the rock which is independent of weak external magnetic fields such as the geomagnetic field. This permanent magnetization has various origins. One very important source of remanent magnetization is the thermo-remanent magnetization (TRM) which arises during the cooling of rocks. This magnetization (often primary) will be fixed in the direction of the earth's magnetic field during the cooling. However, the rocks may acquire a secondary remanent magnetization through later thermal events. Chemical processes influencing the magnetic minerals in the rocks can also be a source of remanent magnetization. In addition, there also exist other types, for example, viscous and isothermal remanent magnetization. The direction of the remanent magnetization reflects the direction of the geomagnetic field present when the remanent magnetization originated. Due to continental drift and polarity changes of the geomagnetic field, the direction of the remanent magnetization is usually different from that of the present geomagnetic field.

The ratio of remanent to induced magnetization is called the Köningsberger ratio (Q-ratio) which is the most usual way of expressing the relative amount of remanent magnetization present in the rock.

The magnetization of a rock is carried by three types of magnetic minerals, namely ferro-, para- and diamagnetic minerals. Rocks mainly consist of para- and diamagnetic minerals. But ferromagnetic minerals such as magnetite have magnetization magnitudes which are in the order of 10^4 to 10^6 times larger than that of the para- and diamagnetic minerals. Pyrrhotite is also a ferromagnetic mineral which has a level of saturation magnetization about 10^2 times less than magnetite. It is also a less common mineral compared with magnetite. Magnetism in most rocks is therefore mainly carried by the ferromagnetic minerals. Even if the ferromagnetic minerals are present in very minute amounts (more than 0.1 vol.%) they will tend to mask the magnetization of the para- and diamagnetic minerals. Rocks dominated by para- or diamagnetic magnetizations have therefore practically no ferromagnetic minerals. The paramagnetic minerals in rocks are mainly iron-rich mafic minerals such as olivine, pyroxene, amphibole, and biotite etc., while the most common diamagnetic minerals are quartz and feldspar. The dominating ferromagnetic mineral in most of the crystalline rocks is magnetite and the magnetization of the rocks will therefore mainly reflect the magnetite content.

The dia- and paramagnetic minerals have no net magnetization without an external magnetic field. In an external magnetic field such as the geomagnetic field, the paramagnetic minerals will have an induced magnetization (c. 10^{-4} cgs) in the direction of the external field, while diamagnetic minerals are magnetized in the opposite direction (c. 10^{-5} cgs).

Ferromagnetic minerals have a spontaneous magnetization, but in the absence of an external field this magnetization will be arranged in domains with different directions of spontaneous magnetization. This serves to decrease the net magnetization. Above a specific temperature (the Curie temperature) for each ferromagnetic mineral the thermal movements will overcome the forces causing the spontaneous magnetization which ceases to exist above the Curie temperature of ferromagnetic minerals (580° C for pure magnetite).

The properties of the ferromagnetic minerals are dependent on the type of the existing domains. Large grains are segregated into several domains which have different directions of spontaneous magnetization, while the smaller grains only have space for one single domain of spontaneous magnetization. These two types of grains are called multidomains (MD) and single domains (SD), respectively.

If an external field acts on the MD grains, the domains in the direction of the field will expand at the expense of the other domains and thus cause a net magnetization in the direction of the external field. In weak external fields, such as the geomagnetic field, the domains will return to their initial condition after removal of the magnetizing external fields (i.e the net magnetization disappears). This growth of the domains with spontaneous magnetization along the external field will result in an induced magnetization along the geomagnetic field. Small magnetite grains with diameters of 0.035–0.057 μm and 0.057–20 μm are carrying magnetization of single- and pseudo-single domain (PSD) types, respectively. The PSD grains contain only a few domains where domain walls constitute a comparatively larger part of the grains. (The domain wall is the part where the spontaneous magnetization gradually changes direction from the spontaneous magnetization of one domain to the magnetization of the adjacent domain.) A weak external field such as the geomagnetic field will only very slightly affect the direction of magnetization of the single- and pseudosingle domains. (This is due to the fact that the domain walls have more difficulties to move in the smaller grains and that the direction of magnetization in the SD grains are strongly blocked in its original direction.) Thus the induced net magnetization along the geomagnetic field is very small.

During cooling of the rock, the present geomagnetic field will cause a slight bias in the orientation of the magnetization towards the direction of the geomagnetic field. If no external field is present, the spontaneous magnetization will have a random orientation without any net magnetization. The magnetization of SD and PSD grains, after cooling below the Curie temperature of the magnetic minerals, will be blocked in their direction, thus causing a thermo-remanent magnetization.

Small grains carrying remanent magnetization of SD and PSD types contribute very little to the total induced magnetization but contribute greatly to the thermoremanent magnetization (TRM). Grain sizes of 0.22μm give a ratio of TRM to induced magnetization of 27 (Dunlop 1972). Induced magnetization is practically independent of grain size for grains larger than 50μm, but decreases rapidly with decreasing grain size (Shandly & Bacon 1963). It is therefore convenient to consider grains of 50μm and larger to be of true MD type (Stacey & Banerjee 1974). The MD grains give a large contribution to induced magnetization and a small contribution to the remanent magnetization. However, they generally carry some viscous soft magnetization.

The type of domain also influences the stability of the remanent magnetization, i.e. the resistance to demagnetization. The most common method to demagnetize collected samples is AC-demagnetization. The samples are demagnetized by applying an alternating magnetic field, where the peak field is increased stepwise until most of the remanent magnetization is lost. MD grains are characterized by a soft and unstable remanent magnetization which is easily demagnetized. SD and PSD grains have a hard and stable remanent magnetization, where resistance against demagnetization increases with decreasing grain size. Dunlop (1973) has carried out AC-demagnetization on synthetic magnetite grains of known grain sizes. By comparing the AC-demagnetization curves against Dunlop's master curves it is possible to get an idea of the grain sizes of the magnetite crystals which carry the remanent magnetization.

MEASURED PETROPHYSICAL PROPERTIES

NORDINGRÅ GABBRO

The gabbros have a rather high content of mafic minerals and therefore also rather high densities. The Nordingrå gabbro has a simple monomodal Gaussian density distribution with a mean value and standard deviation of 3.017± 0.080 g/cm^3 (See Fig. 3 in Larson & Magnusson 1979). The SiO_2 content of 49 wt.% estimated from the mean density (Henkel 1976), is in rather good agreement with the mean value of the chemical analyses which is 50.6 wt.% (G. Lundqvist 1977). The CM/AF-index (Ca+ 1.2 Mg)/(K+1.43 Na) estimated from the mean density is 8 (Henkel 1976) which is considerably higher than the mean value of the chemical analyses which is 3.9 (G. Lundqvist 1977). Thus, the Nordingrå gabbro, which is an Fe-rich gabbro of rapakivi type, has a low CM/AF-index compared with gabbros of similar densities. However, the Nordingrå gabbro has a low content of Ca (10% CaO) and Mg (3.5% MgO) according to G. Lundqvist (1977), compared with the average composition of basic magmas, for example, continental flood basalts (10.0% CaO and 3.5% MgO;Pearce 1974). The alkali content (2.6% Na_2O and 1.4% K_2O) of the Nordingrå gabbro is similar to that of sub-alkalic magmas, but the gabbro falls in the uppermost part of the sub-alkalic region, i.e. it is richer in alkalis than the average sub-alkalic magmas (Middlemost 1975). This will also cause a somewhat lower CM/AF -index. The rather low Mg-content of the gabbro is due to the fact that the olivines and pyroxenes are rather iron-rich (von Eckermann 1938;G. Lundqvist 1977).

The Nordingrå gabbro is characterized by a low susceptibility. The distribution of the susceptibility measurements along profiles across the gabbro shows a simple lognormal Gaussian distribution. The mean value of about 2.0×10^{-4} cgs is close to the paramagnetic region ($<2 \times 10^{-4}$ cgs). The results of the *in-situ* susceptibility measurements are presented in Chapter 7. The Nordingrå gabbro is thus very poor in magnetite and therefore a large part of the magnetization is carried by the paramagnetic minerals. A Curie temperature measurement of one sample using a susceptibility balance bridge resulted in a temperature of about 580° C, the Curie temperature of pure magnetite. Thus, the ferromagnetic minerals in the gabbro are mainly rather pure magnetites. However, Piper (1980) has reported that pyrrhotite can also carry a significant proportion of the magnetization measured in some of the specimens from the Nordingrå gabbro. In the collected samples the induced magnetization is usually larger than the remanent magnetization. The Q-ratios of the samples (Fig. 6) show a simple lognormal Gaussian distribution with a slight skewness towards low Q-ratios. The mean value and standard deviation of the Q-ratios is 0.47 ± 0.42 decades (one decade is one 10 logarithm). The samples have a soft and easily AC-demagnetized remanent magnetization, where most of the remanent magnetization is lost at 50 Oe peak field. As a consequence the gabbro is characterized by a magnetization of the multidomain type. The magnetization of the gabbro is therefore mainly carried by magnetite grains which are 50μm or larger.

The susceptibility *versus* Q-ratio plot shows two trends (Fig. 7);one in the paramagnetic region ($<2 \times 10^{-4}$) and the other in the ferromagnetic region ($>2 \times 10^{-4}$ cgs). In the paramagnetic region there is a slight increase in susceptibility with increasing Q-ratio. The paramagnetic minerals have no spontaneous magnetization and thus no remanent magnetization. Although magnetite occurs in very minute amounts in the paramagnetic region, the occurrence of remanent magnetization proves the presence of ferromagnetic minerals. However, natural paramagnetic minerals generally contain very fine submicroscopic impurities, probably magnetite. This has been established by the magnetic character of separated paramagnetic minerals, which were shown to have both para- and ferromagnetic magnetizations. After pulverization and fractionated magnetic separation of the paramagnetic minerals, even the magnetically weakest fraction was found to contain fine sub-microscopic ferromagnetic impurities (Nagata *et al.* 1957; Chevalier 1958; Akimoto *et al.* 1958; Syono 1960). Thus, the remanent magnetization in the paramagnetic region might be caused by these impurities.

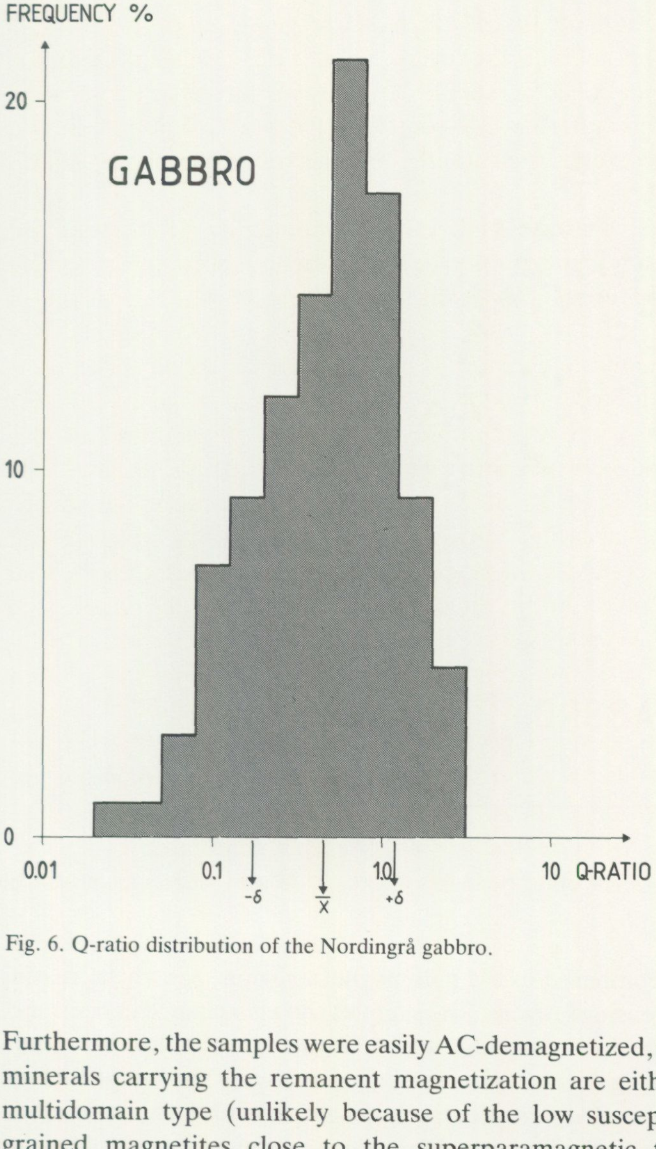

Fig. 6. Q-ratio distribution of the Nordingrå gabbro.

Furthermore, the samples were easily AC-demagnetized, which indicates that the minerals carrying the remanent magnetization are either large grains of the multidomain type (unlikely because of the low susceptibility) or, very fine-grained magnetites close to the superparamagnetic threshold. The superparamagnetic grains also have a soft and easily demagnetized magnetization (Stacey & Banerjee 1974). The trend of increasing susceptibility with increasing Q-ratio in the paramagnetic region might therefore be caused by an increasing amount of ferromagnetic impurities in the paramagnetic minerals.

In the ferromagnetic region the magnetization is mainly carried by ferromagnetic minerals such as magnetite. This is due to the fact that the contribution of the paramagnetic minerals to the overall magnetization is masked by the much higher contribution of the ferromagnetic minerals. The ferromagnetic region shows a

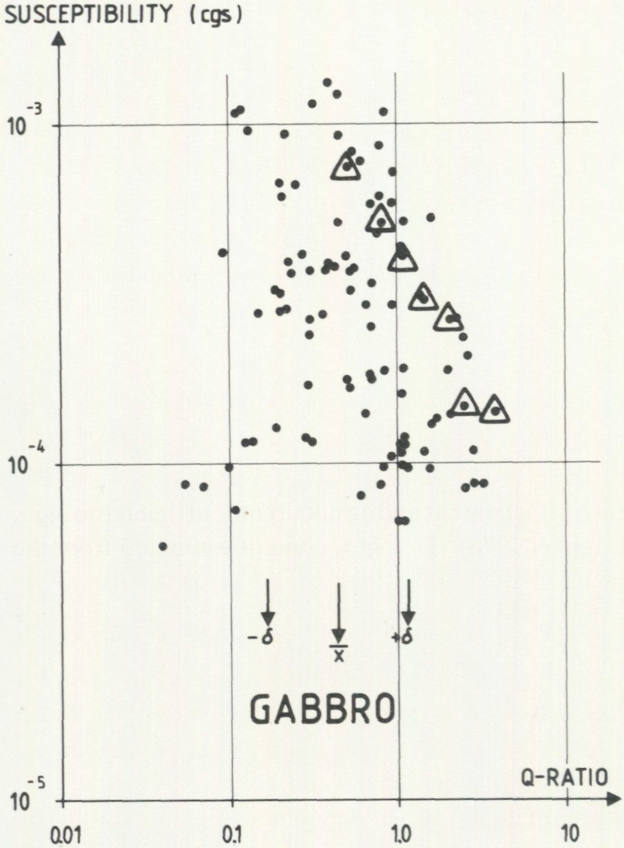

Fig. 7. Susceptibility *versus* Q-ratio of the Nordingrå gabbro. △: selected samples for microscope investigations.

reverse trend (Fig. 7) compared to the paramagnetic region, namely increasing susceptibility with decreasing Q-ratio. The samples show no change in resistance against AC-demagnetization along this trend. This indicates that the grains carrying the remanent magnetization have similar size ranges. The samples have a soft and easily demagnetized remanent magnetization which shows that the magnetites are of the multidomain type. An increasing amount of multidomain grains serves to increase the susceptibility but contributes very little to the remanent magnetization. The ferromagnetic impurities in the paramagnetic minerals, in addition to magnetite grains of single- or pseudosingle domain type, enhance the remanent magnetization more than the multidomain grains. The trend may be explained by the fact that an increasing proportion of magnetization is carried by multidomain grains compared to the ferromagnetic impurities in paramagnetic minerals and small grains of single- and pseudosingle domain type which together make up the main part of the remanent component.

NORDINGRÅ ANORTHOSITE

The high plagioclase content of the Nordingrå anorthosite, which according to G. Lundqvist (1977) varies between 70% and 95%, was probably caused by gravitation during differentiation of a basic magma. The plagioclase has a lower density than the mafic iron-magnesium rich minerals, which has resulted in these anorthosites exhibiting lower densities than for normal basic magmatic rocks (gabbros etc.). The densities of the collected samples show a distribution which can be considered a monomodal Gaussian density distribution with a mean value and standard deviation of 2.796 ± 0.044 g/cm^3 (see Fig. 3 in Larson & Magnusson 1979). However, a few samples have rather high densities which are comparable to the gabbro, thus indicating a less pronounced degree of differentiation. Due to gravity differentiation, the anorthosite has a density comparable to rocks of dioritic to granitic composition. The empirical relation between density, SiO_2 content and CM/AF-index, which was established for differentiated magmatic rocks, will result in this case in a SiO_2 content and an alkali content that is too high, i.e.a lower CM/AF-index (Henkel 1976). The SiO_2 content estimated from the mean density is 58 wt.% which is considerably higher than the mean value of the chemical analysis, namely 51.5 wt.% (G. Lundqvist 1977). The CM/AF-index estimated from the mean density is 1.4 which is considerably lower than the mean value calculated from the chemical analysis which is 3.6 (G. Lundqvist 1977). The CM/AF-index of the anorthosite is similar to that of the gabbro which is 3.9. This is due to the fact that the lower contents of magnesium and potassium are compensated by higher contents of calcium and sodium.

The anorthosite samples have susceptibilities ranging clearly from ferromagnetic values of 10^{-3} cgs to values in the paramagnetic region of $<2\times10^{-4}$ cgs (Fig. 9). The *in-situ* susceptibility measurements show that the anorthosite has two geographically distinct areas which are characterized by different susceptibilities, one with low susceptibility values in the paramagnetic region (mean value of 6.6×10^{-5} cgs) and the other in the ferromagnetic region with susceptibilities of the order of 5×10^{-4} cgs (see Chapter 7). The mean value of 6.6×10^{-5} cgs corresponds to approximately 10 vol.% content of paramagnetic minerals. In conclusion, the anorthosite is rather poor in magnetite with an estimated content ranging from practically absent (the magnetization is mainly carried by paramagnetic minerals) to 1 vol.% magnetite (Balsley & Buddington 1958).

A Curie temperature measurement of one sample showed that nearly all the magnetization was lost above 580° C, which indicates that the magnetization is carried by rather pure magnetite. However, the complex loss in magnetization at lower temperatures (200–300° C) indicates that pyrrhotite might also make a significant contribution to the total magnetization of the sample. Piper (1980), working with some specimens from the Nordingrå anorthosite, also found that pyrrhotite carries a significant proportion of the magnetization.

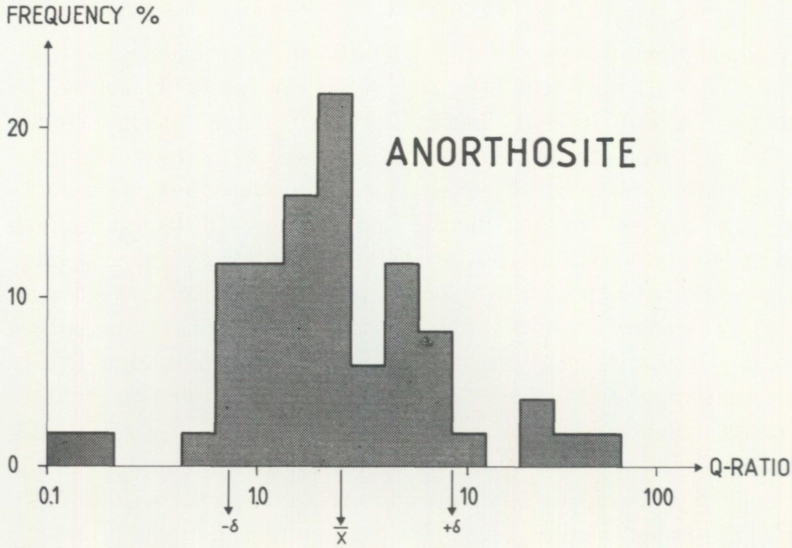

Fig. 8. Q-ratio distribution of the Nordingrå anorthosite.

The investigated samples generally showed a predominance of the remanent magnetization over the induced, the former being as much as 20 to 50 times the latter (this means that Q-ratios are of an order of 20 to 50); only a few samples have Q-ratios below 1. Although the Q-ratios have a rather complex distribution, it can be considered as a lognormal distribution with an estimated mean value and standard deviation of 2.5 ± 0.53 decades;one decade is equivalent to one 10 logarithm (Fig. 8). AC-demagnetization indicates that the magnetites carrying the remanent magnetization range in size from 6 to 0.037 μm, but in most samples the grain sizes are in the range 0.076 to 0.038 μm according to Dunlop's (1973) master curves. Thus, the grain sizes are very small, being below or close to the approximate limit of visibility in reflected light (0.5 μm). This suggests that these grains might be fine-grained exsolution magnetite inclusions in larger host minerals, or, they occur as fine intergrowths with, for example, ulvite or ilmenite.

The susceptibility *versus* Q-ratio plot (Fig. 9) shows a trend of decreasing susceptibility with increasing Q-ratio in the ferromagnetic region (i.e, the main part of the magnetization is carried by the ferromagnetic minerals). Along this trend AC-demagnetization of the samples shows no change in resistance against demagnetization. This indicates that the grains carrying the remanent magnetization have a similar grain size. The samples with high Q-ratios and low susceptibilities have very minute amounts of larger grains of the multidomain type. The dominating magnetite grains in these samples are probably very fine-grained exsolution inclusions in host minerals or fine intergrowths (these grains

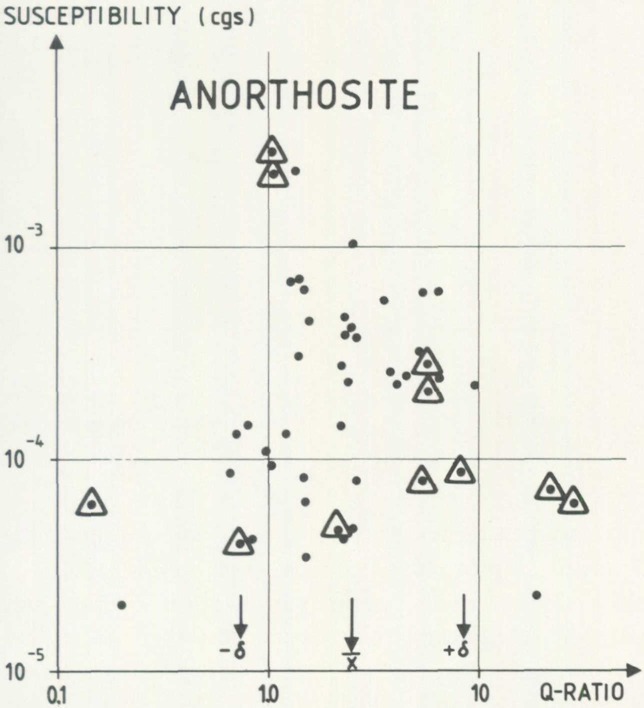

Fig. 9. Susceptibility *versus* Q-ratio of the Nordingrå anorthosite. △: selected samples for microscopic investigations.

carry magnetizations of the single or pseudosingle domain type). The samples with higher susceptibilities and an approximate equal proportion of remanent and induced magnetization (i.e. Q-ratios of about 1), probably contain some larger multidomain magnetite grains which contribute mainly to the susceptibility and very little to the remanent magnetization. Thus the observed trend of decreasing susceptibility with increasing Q-ratio is probably caused by a decreasing proportion of large magnetite grains which have a magnetization of the multidomain type.

In the paramagnetic region (where the magnetization is mainly carried by the paramagnetic minerals) with very low susceptibilities there is a scatter in the Q-ratios (Fig. 9). This scatter is probably due to varying amounts of fine-grained magnetites. These contribute mainly to the remanent magnetization and very little to the susceptibility.

ULVÖ DOLERITE

Even though the dolerite is characterized by rhythmic igneous layering and a resulting variation in chemical and mineralogical composition, samples from the

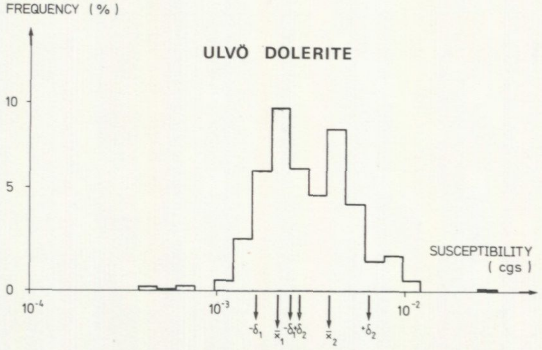

Fig. 10. Distribution of the *in-situ* susceptibility measurements across 4 different dolerite sheets.

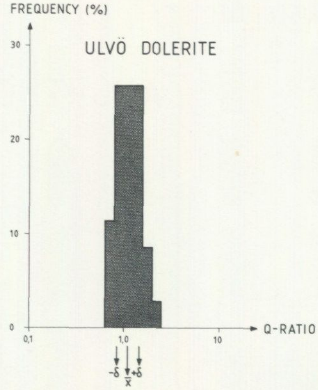

Fig. 11. Q-ratio distribution of the Ulvö dolerite.

chilled margin can be considered to represent the average composition of the magma. A few of the dolerite samples corresponding to iron-enriched layers exhibited very high densities. There are also samples with rather low densities corresponding to the most salic (plagioclase-rich) layers. However, neglecting these samples the dolerite shows a monomodal Gaussian density distribution with a mean value and standard deviation of 3.012 ± 0.040 g/cm^3 (see Fig. 3 in Larson & Magnusson 1979). The SiO_2 content (48 wt.%) estimated from the mean density (Henkel 1976) is somewhat higher than the SiO_2 content (46 wt.%) from the chemical analysis of the chilled margin (Larson 1980). The CM/AF-index (8) estimated from the mean density is also somewhat higher than the CM/AF-index (6) of the chemical analysis from the chilled margin (Larson 1980). The Ulvö dolerite is an alkali basaltic rock which is somewhat richer in alkalies than sub-alkalic basalts (e.g. continental flood basalts; Middlemost 1975).

The rhythmic layering in the dolerite is reflected in the variation of susceptibility and natural remanent magnetization across the sheet, and is also closely related to the modal variation of the opaque Fe-Ti-Mn oxide phases (Larson & Magnusson 1976). The magnetites responsible for the remanent magnetization and the susceptibility show a very similar rhythmic variation, thus the magnetic phases carrying both the remanent and the induced magnetization are closely related (Larson & Magnusson 1976). This is due to the fact that the intergrowth pattern of magnetite-ulvite, which carries the main part of the remanent magnetization, is restricted to areas within the host grains of larger magnetites. The areas with no intergrowth pattern in the larger host magnetite grains carry a magnetization of the multidomain type which mainly contributes to the susceptibility. In this way, the settling grain contain both magnetization of single and pseudosingle domain type in the intergrowth areas and multidomains in the areas without intergrowth patterns (Larson & Magnusson 1976).

The *in-situ* susceptibility measurements across the dolerite sheets show at all sites, except for the large ring-shaped lopolithic intrusion outcropping between Köpmanholmen and Åvikebukten, a lower unit with low and uniform susceptibility and an upper unit with higher and more varying susceptibility (see Chapter 7). The susceptibility distribution therefore shows a bimodal distribution with two frequency maxima (Fig. 10). The lower unit of the sheets has a mean value and standard deviation of 2.0×10^{-3} cgs ±0.12 decades, respectively, whereupon the upper unit has a mean value and a standard deviation of 4.0×10^{-3} cgs ±0.21 decades. Because the lower unit is more uniform it is characterized by a smaller standard deviation.

The dolerite has an approximately equal proportion of remanent and induced magnetization (Q=1). The Q-ratios, which show a lognormal monomodal distribution with a small scatter (Fig. 11), have a mean value and standard deviation of 1.1 ± 0.12 decades, respectively. The remanent magnetization is rather resistant against AC-demagnetization. The estimated grain size is approximately $0.037\,\mu$ to $0.22\,\mu$ (Larson & Magnusson 1976). The intergrowth patterns of ulvite-magnetite, which carries the main part of the remanent magnetization, can only be observed using oil immersion and at magnifications of more than 1000x (Larson & Magnusson 1976). Temperature demagnetization shows that the remanent magnetization is carried by two magnetic mineral; one is ulvite with 30–35 mol-% magnetite in solid solution, and the other is a rather pure magnetite with at most a few mol-% ulvite in solid solution (Larson & Magnusson 1976).

JOTNIAN SANDSTONE

The Jotnian sandstone, which consists mainly of quartz and cloudy fledspar fragments is characterized by a monomodal Gaussian density distribution with a mean value of 2.634 g/cm^3 and a standard deviation of ±0.010 g/cm^3. However, a few sampled arkoses have considerably higher densities (Fig. 12). These arkose samples probably consist of *in-situ* material (regolith) derived partly from Svecokarelian rocks and partly from the sub-Jotnian complex (G. Bergman 1980).

The sandstone samples have very low susceptibilities with a lognormal distribution (Fig. 13). The mean value and standard deviation of the samples is 4.6×10^{-6} cgs ±1.6 decades. Thus the susceptibility is some 10 times weaker than the susceptibility represented by paramagnetic minerals. This is due to very minute amounts of magnetite and paramagnetic minerals. Although the sandstone mainly consists of diamagnetic minerals, the magnetization is positive and thus the main part of the magnetization must therefore be carried by either ferro- or paramagnetic minerals.

Remanent generally exceeds induced magnetization (Q>1) and some samples

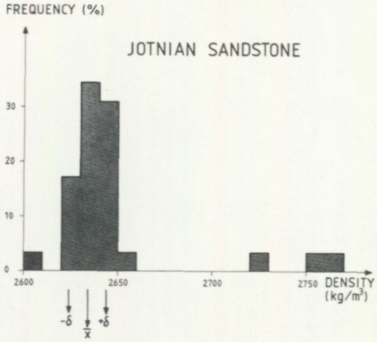

Fig 12. Density distribution of the Jotnian sandstone.

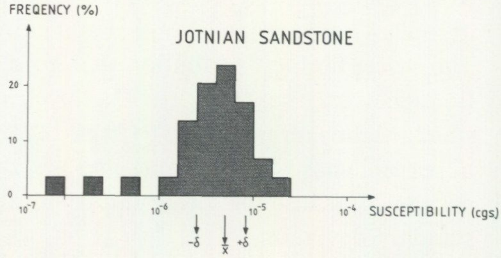

Fig 13. Susceptibility distribution of the Jotnian sandstone.

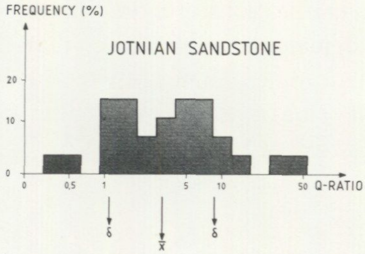

Fig 14. Q-ratio distribution of the Jotnian sandstone.

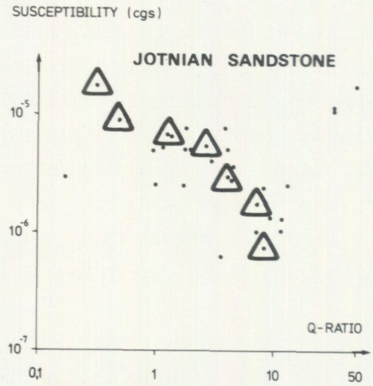

Fig 15. Susceptibility *versus* Q-ratio of the Jotnian sandstone. △: selected samples for microscopic investigations.

can have a Q-ratio of up to 50 (Fig. 14). Even though the samples showed a large scatter in Q-ratio, their distribution was considered to be a lognormal monomodal distribution with a mean value and standard deviation of 3.2 ±0.44 decades (Fig. 11).

The samples have a rather high resistance against AC-demagnetization and they exhibit a coercivity spectra which is typical for magnetite, for example, it is considerably lower than the very high coercivity spectra of hematite. Comparison with the mastercurves of Dunlop (1973), indicates that the grain size varies between 0.037 μm and 0.22 μm. This again indicates that the magnetites carrying the remanent magnetization are very fine-grained and lie close to or below the approximate limit (0.5 μm) of visibility in reflected light. These magnetites are therefore probably exsolution magnetite inclusions in larger host minerals.

Temperature demagnetization of two samples shows that the remanent magnetization is lost at approximately 580° C, showing that magnetite is the carrier.

The plot of susceptibility *versus* the Q-ratio exhibits a trend of increasing susceptibility with decreasing Q-ratio (Fig. 15). The remanent magnetization, which is carried by small amounts of very fine-grained magnetite, shows no change in resistance against AC-demagnetization along this trend. This trend is therefore not an effect of magnetite grain size. Due to the low susceptibility, the amount of large multidomain grains which mainly contribute to the susceptibility must be very small. However, due to the very small amount of ferromagnetic minerals present, the occurrence of paramagnetic minerals, might therefore contribute significantly to the measured susceptibility. The observed trend might therefore be caused by increasing amounts of paramagnetic minerals in the samples. However, the trend might also be due to the fact that an increasing proportion of the magnetization being carried by larger MD grains, even if these grains are present in very small amounts.

IN-SITU SUSCEPTIBILITY

Crystalline rocks mainly consist of para- and diamagnetic minerals. However, in most crystalline rocks the induced magnetization is mainly carried by the ferromagnetic minerals such as magnetite. This is due to the fact that the dia- and paramagnetic minerals have very low induced magnetizations. They will therefore generally give an insignificant contribution to the susceptibility. In rocks which are very poor in magnetite (less than 0.1 vol.%), the susceptibility is mainly carried by para- and diamagnetic minerals. Such rocks have susceptibility values which are less than 2×10^{-4} cgs. Pyrrhotite, which has a susceptibility about 100 times less than that of magnetite, is a less common ferromagnetic mineral than magnetite. The susceptibility measurements will therefore usually reflect the magnetite content in the rock.

The amount of magnetite (Fe-Ti-oxides) present depends upon the initial iron content of the magma, the degree of oxidation and the stage of differentiation. The amount of iron entering into the Fe-Ti oxides depends on various equilibria between the magma and coexisting Fe-bearing minerals which in turn depend upon the oxygen fugacity, temperature and pressure of the magma. Different intrusive phases and varying depths of crystallization might therefore cause a variation in susceptibility.

The magnetic properties also depend on the grain size of the ferromagnetic minerals. Grains of sizes smaller than 50 μm usually have lower susceptibilities than grains of a larger size (Stacey & Banerjee 1974). However, it is the smaller grains that are generally responsible for the larger part of the remanent magnetization. The susceptibility is therefore also influenced by crystallographic intergrowths which divide the host magnetite into smaller units, for example, ilmenite lamellae along the octahedral planes of the magnetite and ulvite-magnetite exsolutions.

THE GABBRO-ANORTHOSITE MASSIF

The aim of measuring the susceptibility was to investigate the possibility of any correlation between susceptibility variations and topographical height, or geographical location within this massif. Such a correlation might be associated either with different phases of intrusion or with different depths of crystallization. Detailed susceptibility investigations might therefore help to map structural features of this intrusion.

The measurements were carried out along profiles (Fig. 3);susceptibility variations over short distances were smoothed by calculating a moving average for the three closest measurements. The moving averages were calculated by including two measurements from the previous average in the calculation of the next.

In order to investigate the susceptibility distributions from different areas, the measurements from various profiles are presented as histograms. Average susceptibility and standard deviation were computed for characteristic parts of the profiles.

The genetic history of the rock, including initial iron content of the magma, differentiation, depth of crystallization and secondary processes, are assumed to be reflected in the susceptibility distribution. This should be characterized by certain mean values and standard deviations. Monomodal distributions are assumed to be caused by a single rockforming process acting on iron-bearing minerals, whilst multimodal distributions might indicate several such processes. Data from 9 000 *in-situ* measurements on gabbro massifs in northern Sweden show that most of the massifs have complex multimodal frequency distributions. However, a few monomodal distributions have been found (L.O. Larson 1977). Rocks are known to have log-normal (log-Gaussian) susceptibility distributions (Tarling 1971) and the investigation of gabbros from northern Sweden by L.O. Larson (1977) shows that the 10 log. gives the best transformation of the susceptibility spectra.

The gabbro-anorthosite massif in Nordingrå has been intruded by an approximately 250 m thick Jotnian dolerite sheet, which covers a large part of the central to eastern part of the area (Fig. 2). The area east of the dolerite sheet consists mainly of anorthosite, while gabbro and anorthosite characterize the area west of the dolerite and east of the Vågsfjärden inlet. The western part of this massif, i.e., the part west of the Vågsfjärden inlet, consists of gabbro (Fig. 2).

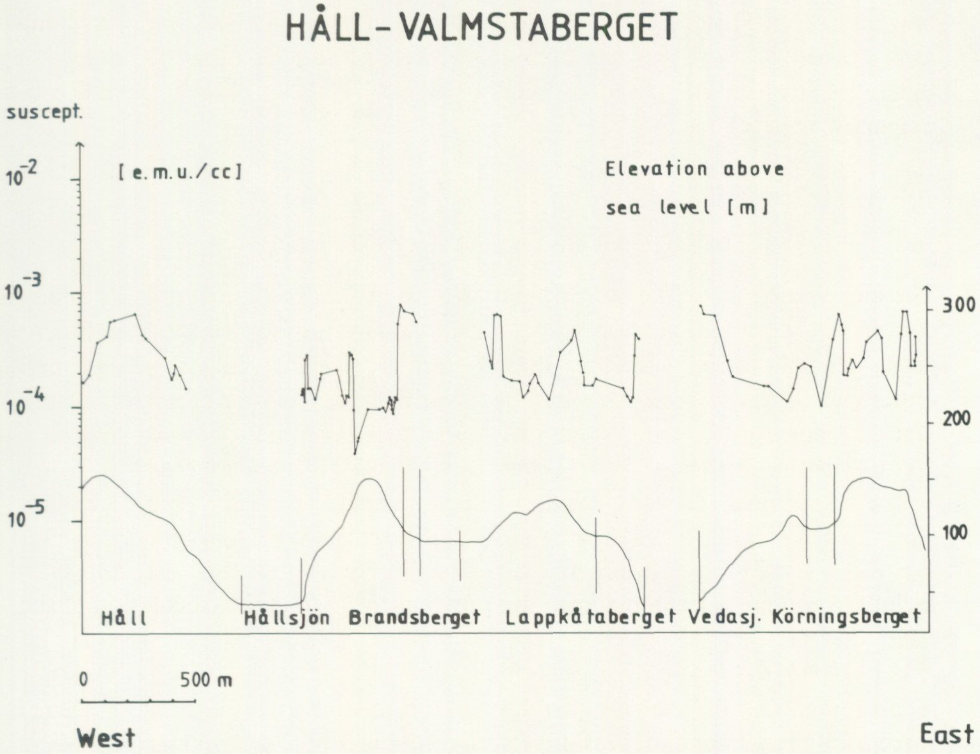

Fig. 16. *In-situ* susceptibility measurements across the gabbro-anorthosite complex from Håll to Valmstaberget. Black dots: measured points in the gabbro; vertical line: topographical lineament; lower graph: elevation above the sea level. For the position of the measured profiles, see Fig. 3.

The gabbro west of the Vågsfjärden inlet is crossed by two west-east profiles (see Fig. 3 for the position of the profiles). The northern profile extends from Håll to Valmstaberget (Fig. 16), whilst the southern profile extends from Sjöbotten and continues to Stortoberget. The southern profile continues from Häggnor to Häggvik east of the Gaviken inlet (Fig. 17), which is one of the most marked morphological lineaments in the area. The gabbro has somewhat higher average susceptibility east of the Gaviken inlet (Fig. 17). When the contact between gabbro and anorthosite is approached at Häggvik, the gabbro has a decreasing susceptibility towards the contact (Fig. 17).

The area east of the Gaviken and Vågsfjärden inlets and west of the dolerite sheet, is crossed by two west-east profiles and one south-north profile (Fig. 3). In this area occur both gabbro and anorthosite (Fig. 2). The northern profile extends from Bergsåker to Ulvviken (Fig. 18), while the southern west-east profile starts at Vågsfjärden and ends at the top of Själandsklinten (Fig. 19). The south-north profile extends from Gåsnäs to lake Omnesjön (Fig. 20); this profile crosses the west-east profiles approximately halfway (Fig. 3).

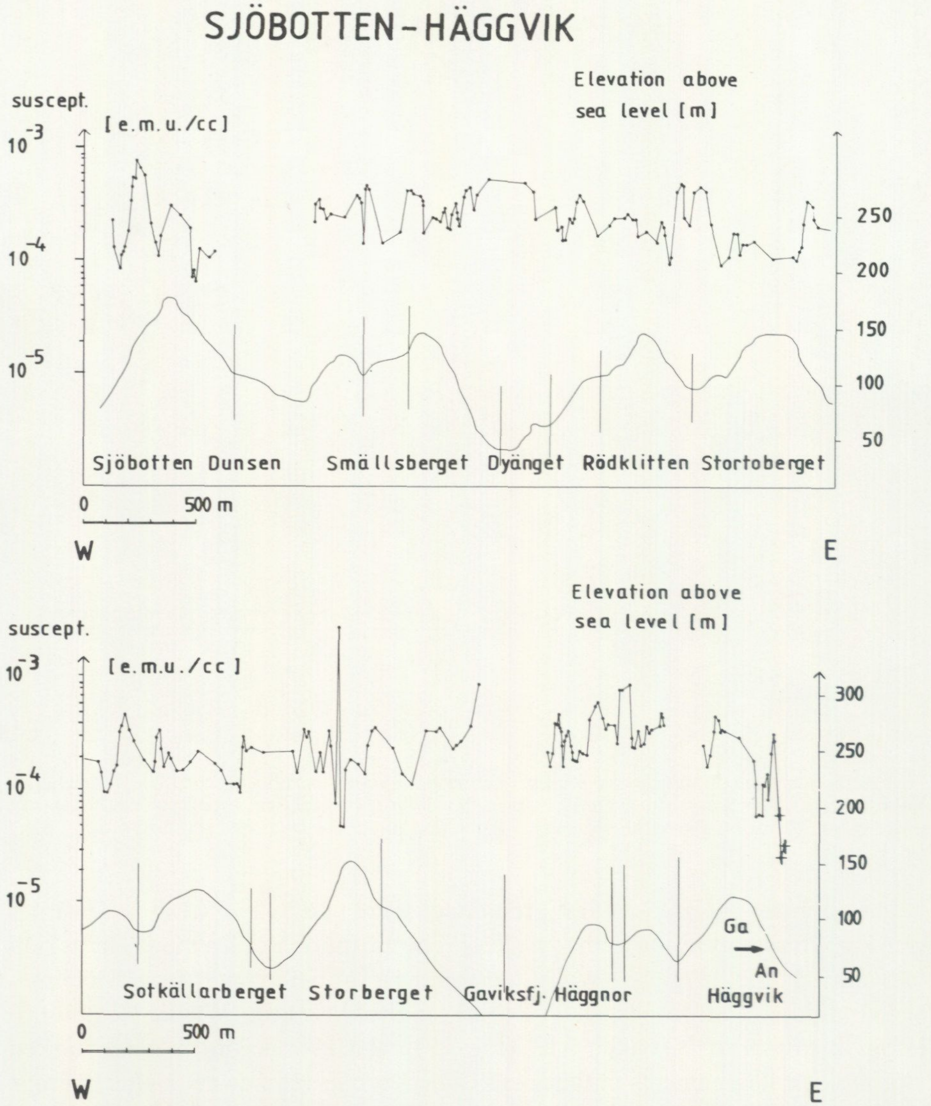

Fig. 17. *In-situ* susceptibility measurements across the gabbro-anorthosite complex from Sjöbotten to Häggvik. Black dots: measured points in the gabbro; X: measured points in the anorthosite; Ga: gabbro; An: anorthosite; arrow: shows the contact between gabbro and anorthosite; vertical line: topographical lineament; lower graph: elevation above the sea level. For the position of measured profiles, see Fig. 3.

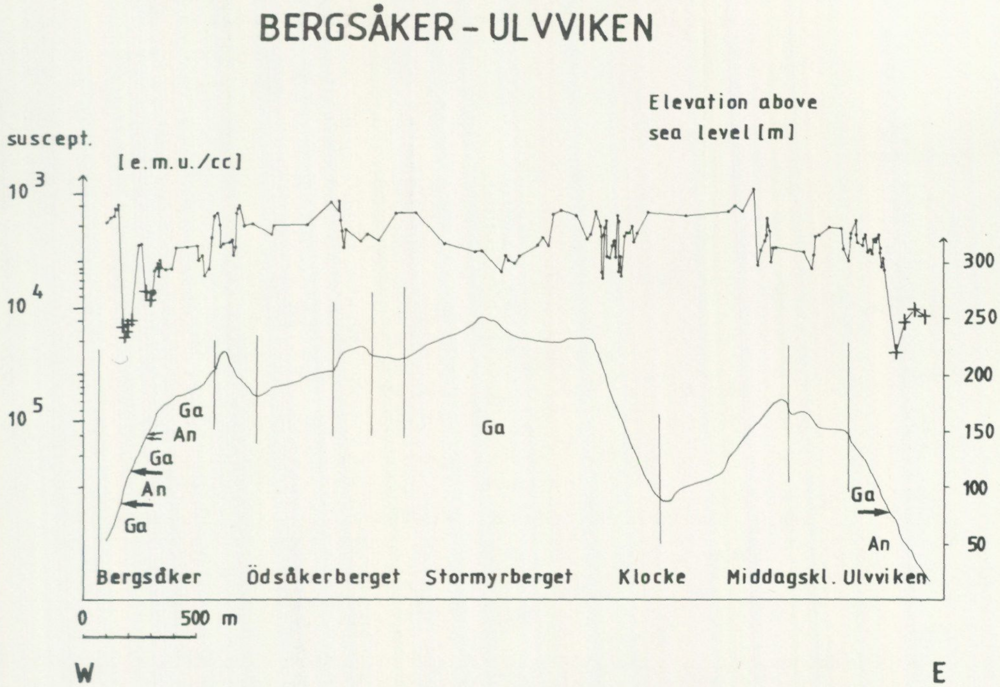

Fig. 18: *In-situ* susceptibility measurements across the gabbro-anorthosite complex from Bergsåker to Ulvviken. Black dots: measured points in the gabbro; X: measured points in the anorthosite; Ga: gabbro; An: anorthosite; arrow shows the contact between gabbro and anorthosite; vertical line: topographical lineament; lower graph: elevation above the sea level. For the position of measured profiles, see Fig. 3.

The Geological Survey of Sweden has measured the susceptibility across Ön peninsula (Figs. 3 and 21). The profiles across Stormyrberget (which is crossed by the northern west-east profile and by the south-north profile) and Ön peninsula, situated in the northern part of the area west of the dolerite sheet, show a somewhat higher average susceptibility in the gabbro compared with the other areas. These profiles also show a decreasing susceptibility in the gabbro as the contact between gabbro and anorthosite is approached (Figs. 18, 20 and 21). In contrast, Ulandsberget and Klösberget (which are crossed by the southern west-east profile and by the south-north profile) show no visible trend of decreasing susceptibility as the contact between gabbro and anorthosite is approached. Apart from the afore-mentioned trends, the profiles across the gabbro show no visible correlation with topographical height or geographical location.

The anorthosite west of the dolerite sheet shows a slightly increasing susceptibility (from 5×10^{-5} cgs to 3×10^{-4} cgs towards east, from Gåsnäs to Själandsklinten (Figs. 19 and 3). In addition, the anorthosite present on the Ön peninsula, which is situated at the eastern part of the area west of the dolerite sheet

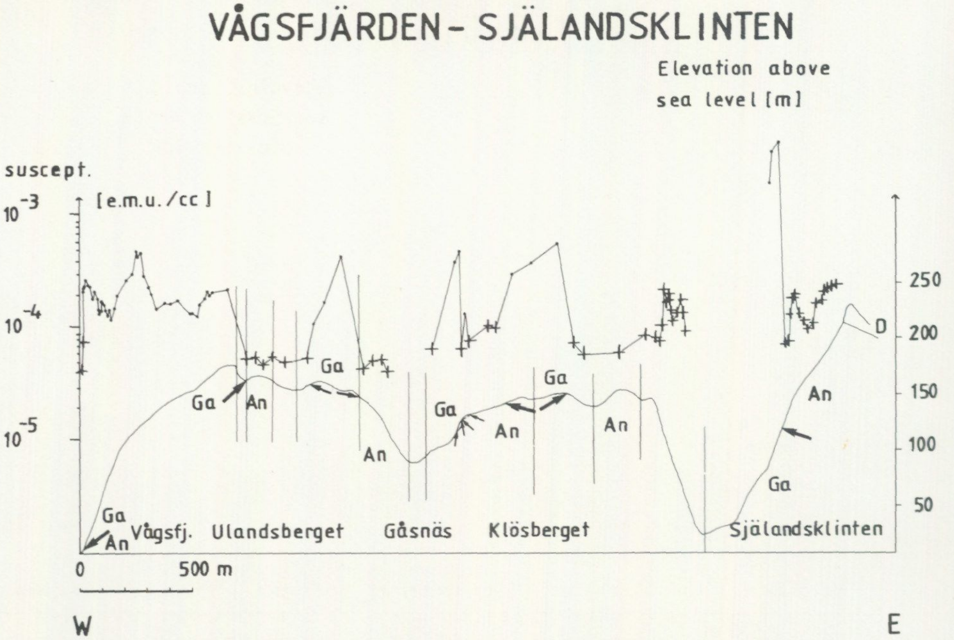

Fig. 19. *In-situ* susceptibility measurements across the gabbro-anorthosite complex from Vågsfjärden to Själandsklinten. Black dots: measured points in the gabbro; X: measured points in the anorthosite; Ga: gabbro; An: anorthosite; arrow: shows the contact between gabbro and anorthosite; vertical line: topographical lineament; lower graph: elevation above the sea level. For the position of measured profiles, see Fig. 3.

(Fig. 3), has an average susceptibility similar to the susceptibility at Själandsklinten (Fig. 21). Where the profiles traverse the contact between gabbro and anorthosite, the gabbro occurs at higher topographical levels than the anorthosite, except at Själandsklinten. For example, Klösberget consists of anorthosite capped by gabbro, which constitutes the hilltop. Also, Ulandsberget has gabbro outcropping at higher topographical level than the surrounding anorthosite (Figs. 2,3,19 and 20). As a general observation, if the contacts are rather flat, the gabbro seems to be overlying the anorthosite in this part of the area.

The area east of the dolerite sheet differs from the western area in that it consists mainly of anorthosite with only minor outcrops of gabbro, which are generally found at low topographical levels. The area is crossed by two west-east profiles, one more northerly profile at the Rävsön peninsula and another one which runs from Älgsjöberget to Bönhamn (Fig. 3). The profiles across this part of the anorthosite have susceptibility values about 10 times higher when compared to the average susceptibility in the anorthosite to the west of the dolerite sheet (Figs. 22 and 23). The central part of the Bönhamn profile has susceptibility values which are similar to those across Rävsön, whilst to the east and west the Bönhamn profile

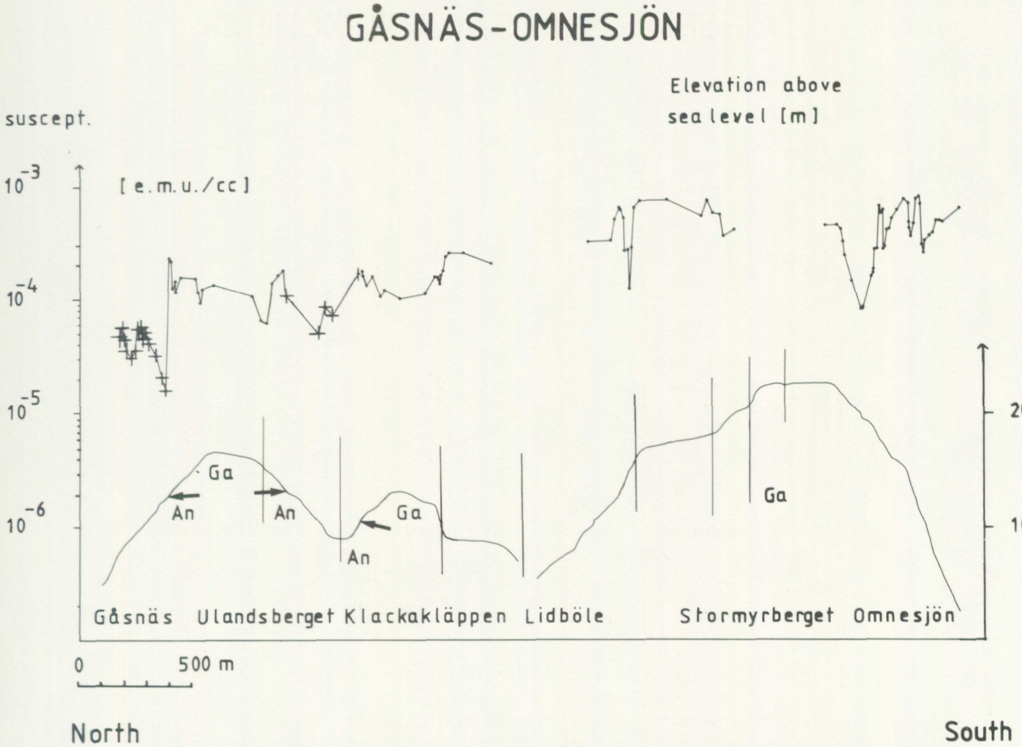

Fig. 20. *In-situ* susceptibility measurments across the gabbro-anorthsite complex from Gåsnäs to Omnesjön. Black dots: measured points in the gabbro; X: measured points in the anorthosite; Ga: gabbro; An: anorthosite; arrow: shows the contact between gabbro and anorthosite; vertical line: topographical lineament; lower graph: elevation above the sea level. For the position of measured profiles, see Fig. 3.

has somewhat lower susceptibility values compared to Rävsön (Figs. 22 and 23).

The susceptibility of the gabbro shows, except for one profile, rather simple and similar distributions which can be considered to be monomodal (Figs. 24, 25, 26 and 27). The bimodal distribution of the Håll-Valmstaberget profile (Fig. 3) has two well-defined frequency maxima, one major frequency maximum similar to the frequency maxima of the other profiles and one minor maximum at a higher susceptibility (Fig. 24). The higher susceptibility maximum might be an effect of igneous layering, which has been observed at a few locations in the gabbro (G. Lundqvist 1976). The higher values may refer to horizons enriched in mafic minerals and magnetite. A higher magnetite content might also be due to an increasing degree of serpentinization (cf. Chapter 8). In general, however, magnetite enriched horizons do not form a common feature in the gabbro. The statistical parameters of the profiles have been estimated by plotting on Gaussian transformation diagrams. The bimodal distribution of the Håll-Valmstaberget

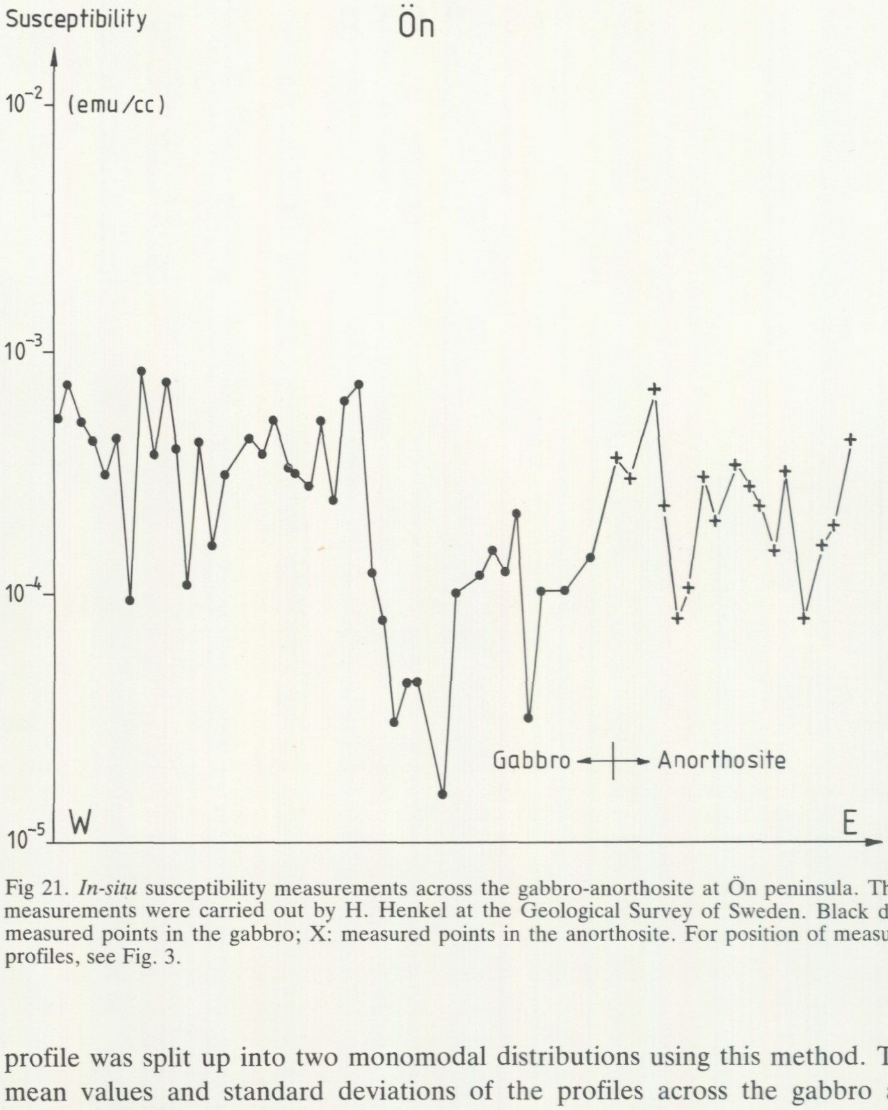

Fig 21. *In-situ* susceptibility measurements across the gabbro-anorthosite at Ön peninsula. These measurements were carried out by H. Henkel at the Geological Survey of Sweden. Black dots: measured points in the gabbro; X: measured points in the anorthosite. For position of measured profiles, see Fig. 3.

profile was split up into two monomodal distributions using this method. The mean values and standard deviations of the profiles across the gabbro are presented below.

Håll-Valmstaberget: 2.0×10^{-4} cgs ±0.30 decades (one decade is one 10 logarithm) and 6.6×10^{-4} cgs ±0.13 decades.

Sjöbotten-Häggvik: 2.2×10^{-4} cgs ±0.32 decades.

Bergsåker-Ulvviken and Lidböle-Omnesjön: 3.7×10^{-4} cgs ±0.29 decades.

Vågsfjärden-Själandsklinten and Gåsnäs-Lidböle: 1.8×10^{-4} cgs ±0.22 decades.

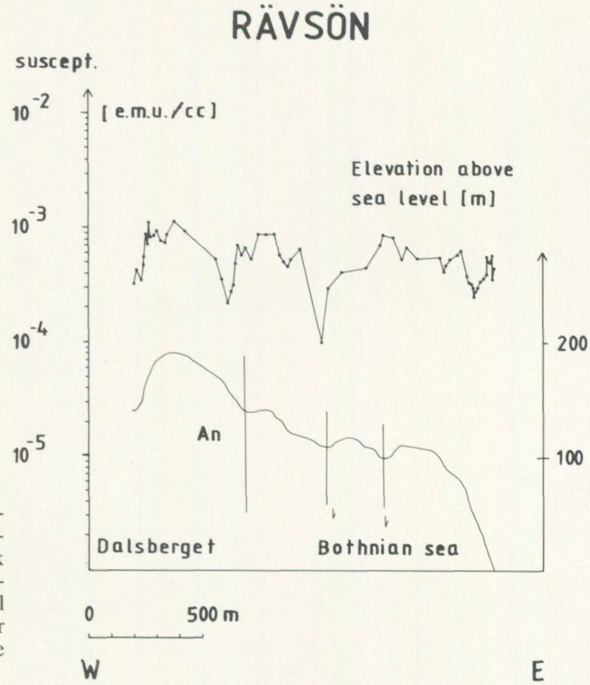

Fig. 22. *In-situ* susceptibility measurements across the gabbro-anorthosite complex at Rävsön. Black dots: measured points in the anorthosite; An: anorthosite; vertical line: topographical lineament. For position of measured profiles, see Fig. 3.

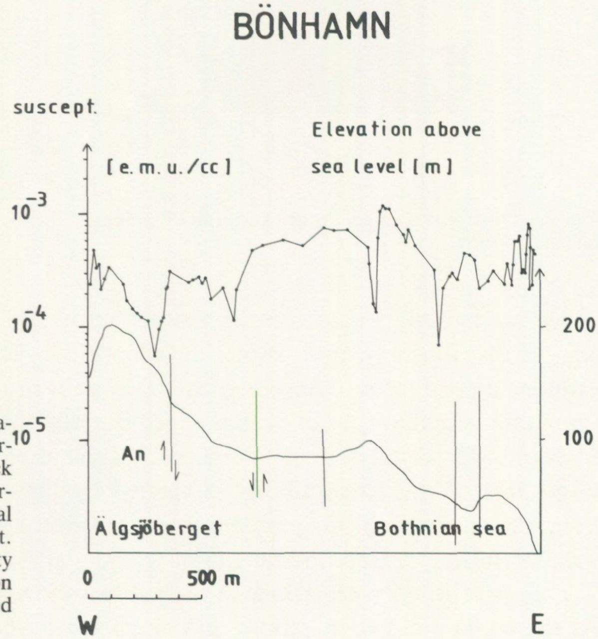

Fig. 23. *In-situ* susceptibility measurements across the gabbro-anorthosite complex at Bönhamn. Black dots: measured points in the anorthosite; An: anorthosite; vertical line: topographical lineament. ↿⇂ : fault established by a gravity survey (Larson & Magnusson 1979). For position of measured profiles, see Fig. 3.

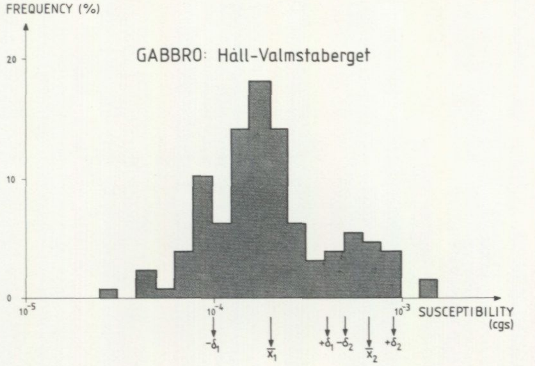

Fig. 24. Distribution of the *in-situ* susceptibility measurements across the gabbro. The Håll-Valmstaberget profile.

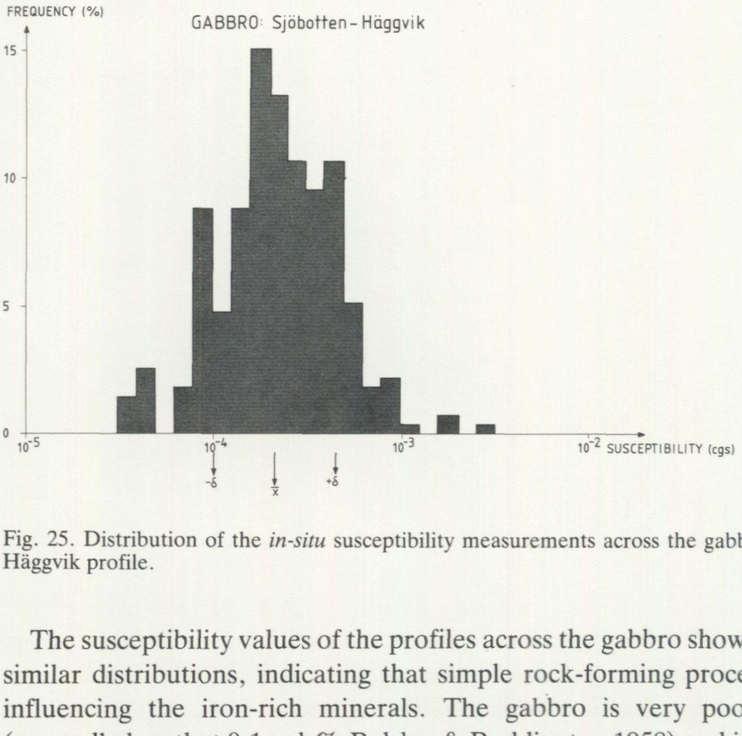

Fig. 25. Distribution of the *in-situ* susceptibility measurements across the gabbro. The Sjöbotten-Häggvik profile.

The susceptibility values of the profiles across the gabbro show as a whole very similar distributions, indicating that simple rock-forming processes have been influencing the iron-rich minerals. The gabbro is very poor in magnetite (generally less that 0.1 vol.%;Balsley & Buddington 1958) and it has an average susceptibility which is close to the paramagnetic region ($<2\times10^{-4}$ cgs). Thus, a large part of the susceptibility is carried by the paramagnetic minerals. The horizons enriched in magnetite have a magnetite content of approximately 1 vol.% (Balsley & Buddington 1958).

The susceptibility variations in the gabbro show some characteristic features. At the contact between gabbro and anorthosite, the gabbro contains a zone of

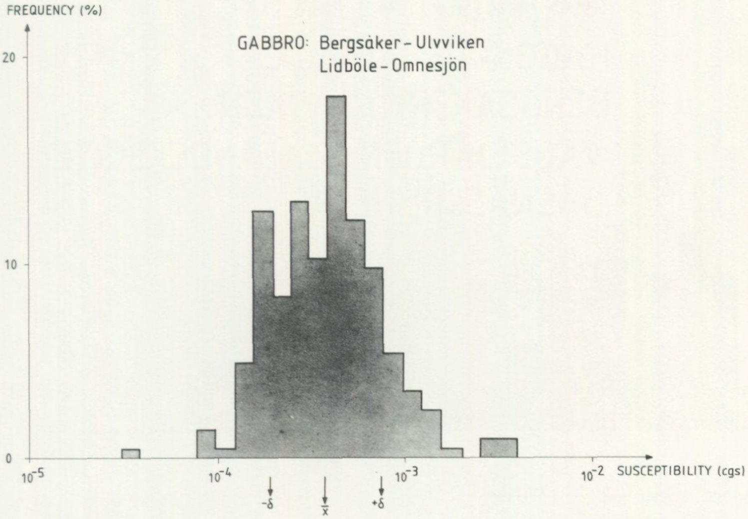

Fig. 26. Distribution of the *in-situ* susceptibility measurements across the gabbro. The Bergsåker-Ulvviken and Lidböle-Omnesjön profiles.

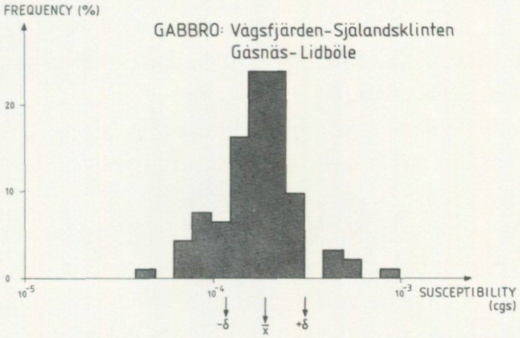

Fig. 27. Distribution of the *in-situ* susceptibility measurements across the gabbro. The Vågsfjärden-Själandsklinten and Gåsnäs-Lidböle profiles.

decreasing susceptibility towards the contact;close to the contact the gabbro has values of about 1.0×10^{-4} cgs. However, the profile from Vågsfjärden to Själandsklinten, which transverses an outcrop sequence of gabbro and anorthosite, shows no obvious trend of decreasing susceptibility towards the contact. This might be explained by the fact that the profile probably transverses the gabbro in a stratigraphical position which in all locations is close to the contact. The lower susceptibility in the contact zone is mostly due to a decreasing content of paramagnetic minerals towards the contact. This is probably caused by a gradual differentiation of the gabbro towards the anorthosite contact, that is, the two rocks gradually merge into each other. Another cause may be mixing of the

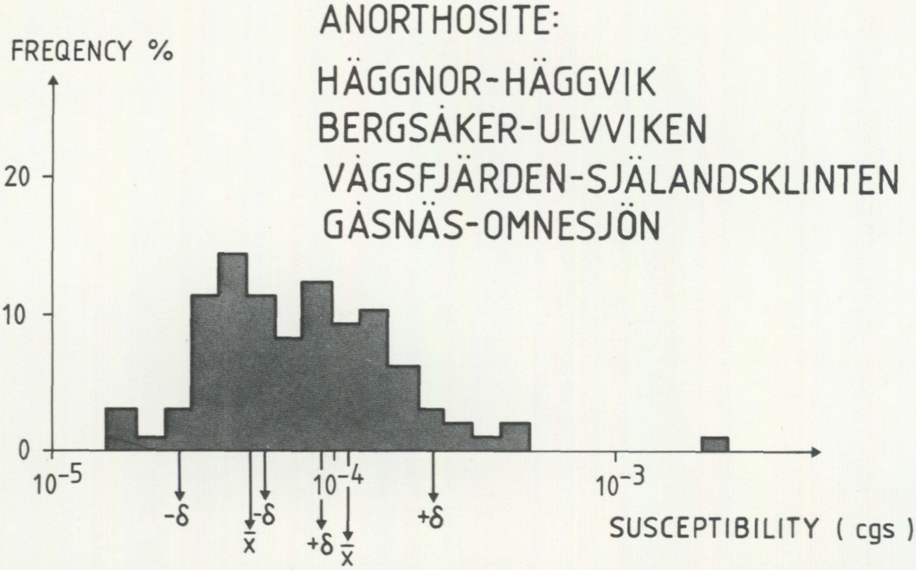

Fig. 28. Distribution of the *in-situ* susceptibility measurements across the anorthosite. The Häggnor-Häggvik, Bergsåker-Ulvviken, Vågsfjärden-Själandsklinten and Gåsnäs-Omnesjön profiles.

gabbro and anorthosite;both differentiation and mixing textures can be observed in field (von Eckermann 1938; G. Lundqvist 1977).

On the west side of the most marked morphological lineament along the Gaviken and Vågsfjärden inlets the gabbro has an average susceptibility of c. 2.1×10^{-4} cgs. No anorthosite occurs in this area.

Across Stormyrberget and the Ön peninsula, the gabbro has a slightly higher susceptibility (c. 3.7×10^{-4} cgs) when compared to the rest of the investigated area. The observed variation in the gabbro might be stratigraphical in effect. In other words, the contact zone of the gabbro is characterized by a low susceptibility (c. 1.0×10^{-4} cgs). This zone shows a gradual transition into a unit which exhibits the highest average susceptibility (3.7×10^{-4} cgs);at a greater distance from the contact (i.e. west of the Gaviken and Vågsfjärden inlets) a unit with somewhat lower average susceptibility (2.1×10^{-4} cgs) is encountered.

The susceptibility values across the anorthosite in the eastern part of the area, west of the dolerite sheet, show an increase towards the east (from Gåsnäs to Själandsklinten). These susceptibility values have a mean value and standard deviation of 1.3×10^{-4} cgs ±0.30 decades. The anorthosite west of the dolerite sheet is defined by low susceptibility values at the western margin of the anorthosite, that is, in the area close to the gabbro contact. This part of the area has a mean value and standard deviation of 5.2×10^{-5} cgs ±0.25 decades. Therefore, the susceptibility values across the anorthosite west of the dolerite sheet show a bimodal distribution with two frequency maxima (Fig. 28).

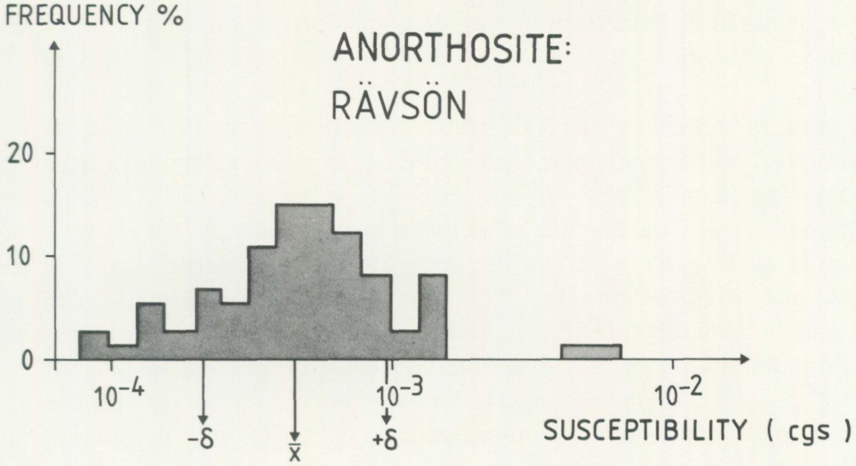

Fig. 29. Distribution of the *in-situ* susceptibility measurements across the anorthosite at Rävsön.

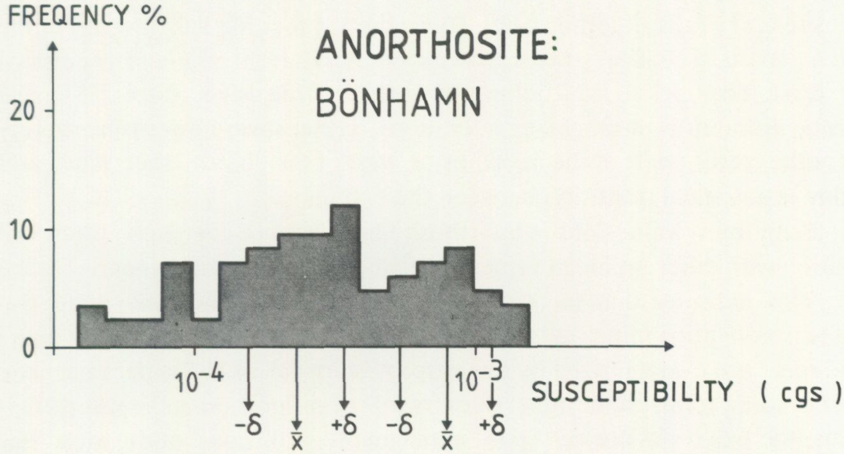

Fig. 30. Distribution of the *in-situ* susceptibility measurements across the anorthosite at Bönham.

The anorthosite east of the dolerite sheet has susceptibility values which are about 10 times higher than those in the area west of the dolerite sheet. The profile across Rävsön peninsula shows a susceptibility distribution of monomodal character with a skewness towards low susceptibility and a few very high susceptibility values (Fig. 29). The susceptibility values at Rävsön have a mean value and standard deviation of 4.5×10^{-4} cgs ± 0.33 decades. At Bönhamn the profile shows a bimodal susceptibility distribution and a skewness towards low susceptibility values (Fig. 30). The bimodal susceptibility is due to the fact that the central part of the profile has higher susceptibility values (Fig. 23). The distribution has been divided into two monomodal distributions with mean values and standard deviations of 2.3×10^{-4} cgs ±0.17 decades and 7.8×10^{-4} cgs ±0.16 decades.

The western margin of the anorthosite outcrop has very low susceptibility values. Here it is deficient in magnetite and the susceptibility is mainly carried by the paramagnetic minerals. The susceptibility mean value of 5.2×10^{-5} cgs corresponds to a paramagnetic mineral content of about 10 vol.%. The anorthosite at the eastern part of the area, west of the dolerite sheet, has an eastward increasing susceptibility. This is an effect of an increasing content of ferromagnetic minerals (mainly magnetite) in the anorthosite. The anorthosite east of the dolerite sheet has susceptibility values of ferromagnetic magnitudes ($>2\times10^{-4}$ cgs), i.e., the susceptibility is dominated by the ferromagnetic minerals (the paramagnetic minerals give an insignificant contribution to the susceptibility). Thus, the anorthosite in the area east of the dolerite sheet has a higher content of magnetite compared with the anorthosite west of the dolerite sheet. The anorthosite at the western margin must therefore be associated with different rock-forming processes influencing the iron-bearing minerals in contrast to the anorthosite east of the dolerite sheet. This indicates that the anorthosites in the two areas could, 1, differ stratigraphically (i.e. different physical conditions during crystallization) or, 2, belong to different intrusive phases, 3, have undergone different post-magmatic alterations. The eastward increasing susceptibility at the eastern part of the anorthosite, west of the dolerite sheet, indicates that there is a gradual transition between the two units.

The susceptibility values of the anorthosite have a more complex multimodal distribution with different mean values and standard deviations compared to the gabbro. This indicates that more complex rock-forming processes have influenced the iron-bearing minerals. Both the gabbro and the anorthosite west of the dolerite sheet are characterized by low susceptibility values in the paramagnetic region, i.e., the paramagnetic minerals carry a large proportion of the susceptibility. Thus, the two rocks are very poor in magnetite in this part of the area. The lower average susceptibility in the anorthosite is due to the fact that the anorthosite has a lower content of paramagnetic minerals. Also the gabbro has a zone containing a decreasing amount of paramagnetic minerals towards the contact between gabbro and anorthosite. These facts indicate that the gabbro and anorthosite have an intimate genetic relationship.

ULVÖ DOLERITE

The aim of measuring the susceptibility across the dolerite sheet was to investigate whether multiple intrusions can be detected. The investigations were therefore carried out where previous petrochemical studies (Lundqvist & Samuelsson 1973;Larson 1980) have established multiple intrusion. Profiles were also

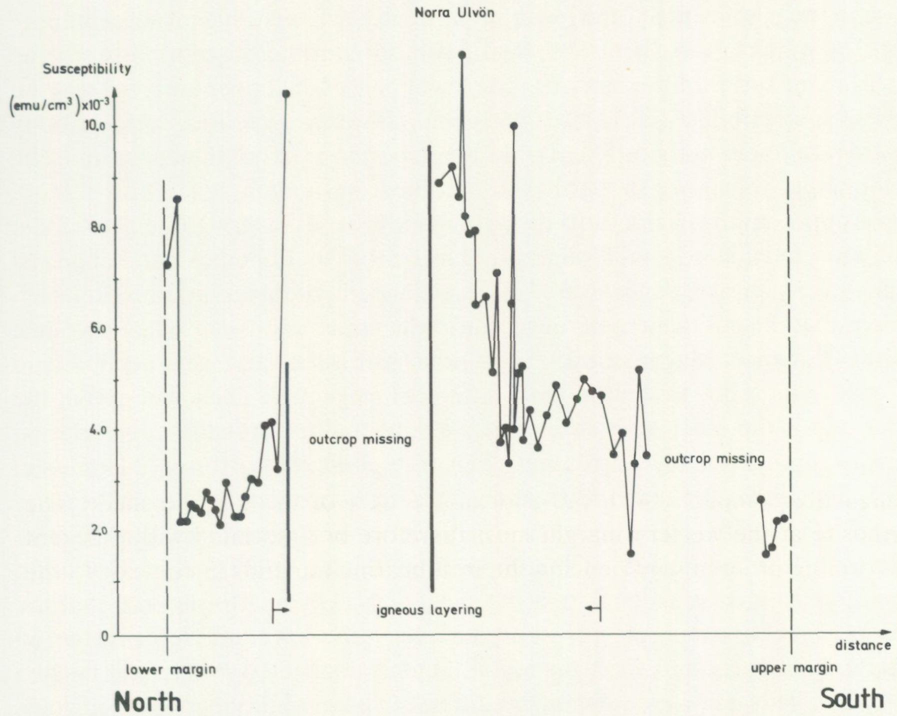

Fig. 31. *In-situ* susceptibility measurements across the dolerite sheet at Norrsand (N. Ulvön). Vertical line: topographical lineament. For position of profiles, see Figs. 1 and 4.

measured elsewhere across the sheet in order to establish the extent of a multiple intrusion character (Figs. 1 and 3). This study was also used as a method for analysing the relationships between various dolerite sheets. Gravity profiles have also been determined across the dolerite sheet at the Ulvö Islands, Rypskär and Edsätterfjärden (Larson & Magnusson 1979). This was carried out in order to detect faults causing stratigraphical displacements in the sheet and to calculate the thickness and dip of the sheet.

The investigation by Thoring & Abrahamsen (1980) of the magnetic properties of Permian dykes in Bohuslän county shows that multiple intrusions can be detected by susceptibility measurements. These dykes consist of multiple intrusions with a marginal dolerite contact zone, followed by a marginal rhomb porphyry and a central rhomb porphyry. These three zones are characterized by different susceptibilities, remanent magnetizations and Q-ratios.

Three profiles were measured across the c. 250 m thick dolerite sheet (Larson & Magnusson 1979) on the Ulvö Islands (N. Ulvön, Ulvösundet and S. Ulvön;see Figs. 1 and 4). The profile at N. Ulvön (Norrsand) exhibits a lower unit (about 30 m thick) characterized by low and uniform susceptibility values (c. 2×10^{-3} cgs) and an upper unit (about 220 m thick) with a higher and more varying susceptibility.

Close to the basal contact, the lower uniform unit exhibits a higher susceptibility (Fig. 31), which has also been observed in some of the other susceptibility profiles (Ulvösundet and Edsätterfjärden). The lower part of the upper unit registers the highest susceptibility (c. 12×10^{-3} cgs) and shows a decreasing susceptibility towards the upper margin (Fig. 31). In the uppermost part of the upper unit, the susceptibility values are similar to those of the lower unit.

The upper unit is characterized by rhythmic igneous layering due to a modal variation of femic and salic minerals (Larson 1973). Euhedral and subhedral magnetite crystals are concentrated in the melanocratatic layers and it is therefore evident that the enrichment of magnetite in the upper unit is caused by rhythmic settling (Larson & Magnusson 1976). In other words the varying susceptibility in the upper unit is due to the rhythmic settling of magnetite. The lower part of the upper unit is the most magnetite enriched zone and towards the upper margin there is a progressively decreasing magnetite content (Larson & Magnusson 1976). This indicates that the rhythmic settling process of the magnetite was strongest in its initial phase and then slowly decreased as more crystals settled as a crystal mush at the bottom of the upper unit. Larson (1980) has carried out a petrochemical investigation across the sheet at N. Ulvön. He suggests that the dolerite sheet has a multiple intrusion character with a lower unit representing an initial magma surge and an upper unit intimately connected with a later magma surge. The two units, established by different susceptibility patterns, coincide with the chemically established multiples. The lower intrusion is thus characterized by low and uniform susceptibility values and the upper by higher and more varying susceptibility values (Fig. 31). Two morphologically distinct lineaments (Fig. 4) cut the dolerite sheet, although from the gravity survey (Larson & Magnusson 1979) it is evident that faulting has not caused any drastic displacements.

The other profiles at the Ulvö Islands (Ulvösundet and S. Ulvön) exhibit a similar susceptibility pattern, i.e., a lower unit with low and uniform susceptibility values and an upper unit with higher and more varying susceptibility values (Figs. 32 and 33). However, the lower unit at Ulvösundet is approximately twice as thick as at N. Ulvön. This is probably an effect of stratigraphical displacement caused by faulting of the lower unit which is cut by a very marked lineament (Fig. 4) whereupon the block to the west seems to be downfaulted. This would cause a repitition of parts of the lower unit, which would therefore appear thicker.

The dolerite sheet at S. Ulvön (Fig. 4) is cut by several faults causing stratigraphical displacements. The gravity survey (Larson & Magnusson 1979) and the susceptibility pattern show that the southern tip of S. Ulvön is a downfaulted block. Along the coast at the south-west side of the island the measurements north of the fault are in the lower uniform unit, whilst the stratigraphical position south of the fault is in the lower magnetite enriched zone representing the upper layered unit (Fig. 33). Along the eastern side of the island,

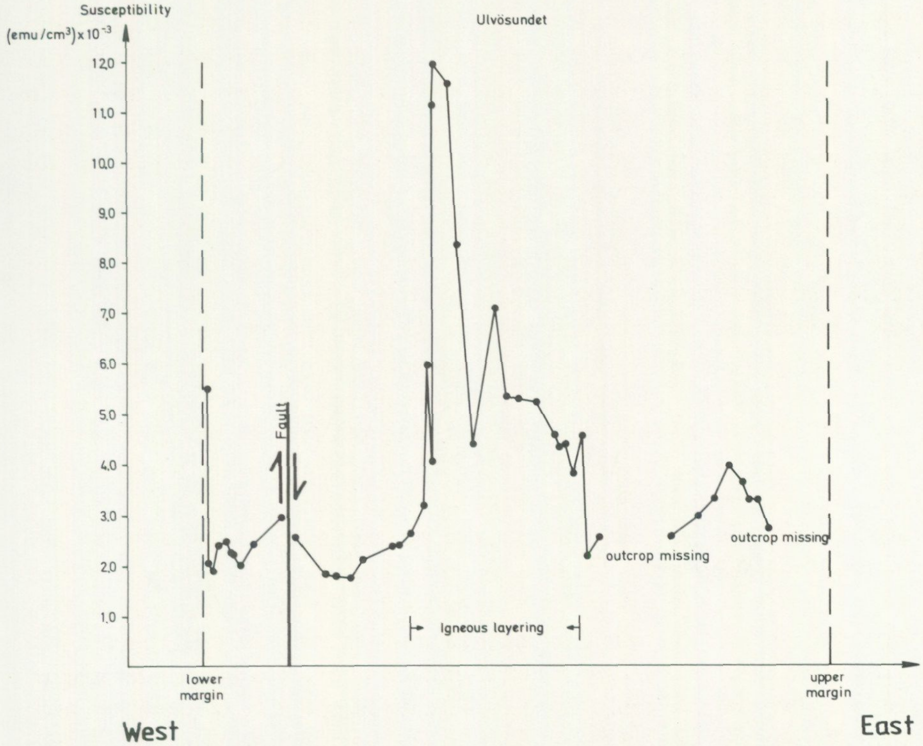

Fig. 32. *In-situ* susceptibility measurements across the dolerite sheet at Ulvösundet. Vertical line: topographical lineament, ↑|↓ : fault. For position of profiles, see Figs. 1 and 4.

the stratigraphical position in the uplifted block north of the fault also represents the lower magnetite enriched zone of the upper unit. This stratigraphical repetition within the sheet results in two zones with high susceptibilities (Fig. 33). The gravity data show that the sheet close to the upper margin is a downfaulted block (Larson & Magnusson 1979).

Three profiles were measured at Nordingrå (Ringkallen, Älgsjö and Rävsön; see Figs. 1,2 and 3). The susceptibility pattern across the approximately 250 m thick dolerite sheet (Lundqvist & Samuelsson 1973) at Ringkallen shows that the sheet comprises two units, a lower unit (about half the thickness of the sheet) characterized by uniform susceptibility values and an upper unit with higher and more varying susceptibility values. These two units coincide with the two distinct units earlier recognized petrochemically (Lundqvist & Samuelsson 1973). The lower unit coincides with the lower Ringkallen multiple, which is more uniform in texture and modal composition, whilst the upper coincides with the more fractionated multiple, strongly affected by crystal settling. Rhythmic layering is also only present in the upper unit (Lundqvist & Samuelsson, op. cit.). The lower unit at Ringkallen has similar susceptibility values to those of the lower unit at the

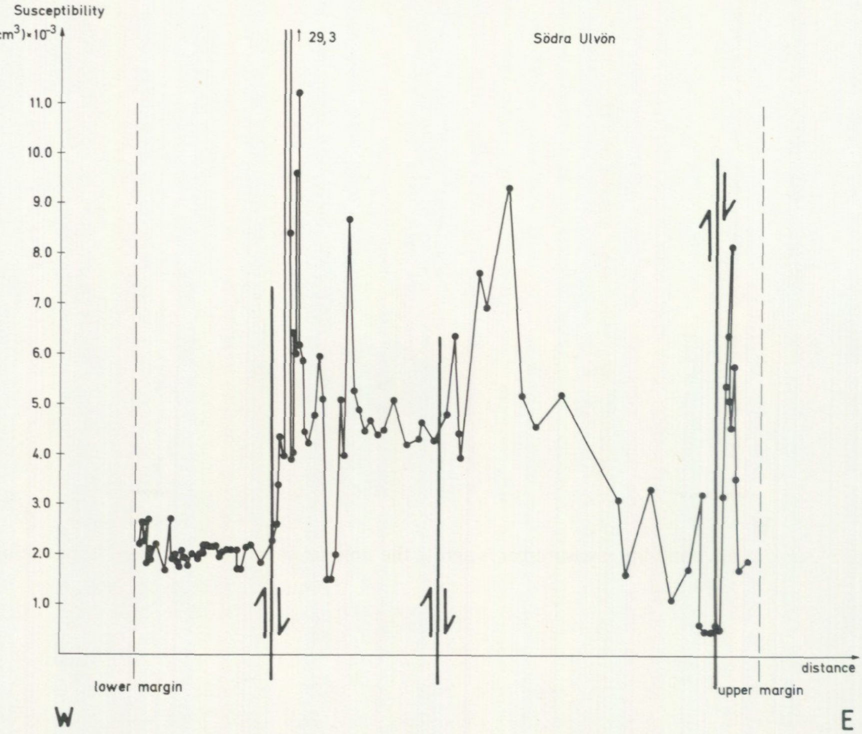

Fig. 33. *In-situ* susceptibility measurements across the dolerite sheet at S. Ulvön. Vertical line: topographical lineament, ↿⇂ : fault. For position of profiles, see Figs. 1 and 4.

Ulvö Islands (c. 2×10^{-3} cgs), but it is much thicker (c. 120 m compared to the 30 m; Fig. 34). The lower magnetite enriched zone of the upper unit at Ringkallen has lower susceptibility values [about $(5–6)\times10^{-3}$ cgs] compared with the corresponding zone at the Ulvö Islands [$(12–29)\times10^{-3}$ cgs]. The upper unit at Ringkallen also exhibits a decreasing susceptibility towards the upper margin.

The other profiles measured across the dolerite sheet at Nordingrå have susceptibility patterns which are very similar to the patterns obtained at Ringkallen (Figs. 35 and 36), i.e., a lower unit with low and uniform susceptibility and an upper unit with a higher and more varying susceptibility. However, the upper unit at Edsätterfjärden (Fig. 35) shows a more disturbed susceptibility pattern which might be caused by a slumping of the crystal mush. Slumping of the crystal mush has been observed by Larson (1980) who stated (p.157): "In one case, laminated feldspars are seen in a dyke-like part within the dolerite east of Älgsjö. This must be caused by flowage, probably by slumping of the crystal mush after deposition of the feldspars"–. The multiple intrusion character is also evident from the break in the trend of the An content of plagioclase as well as in

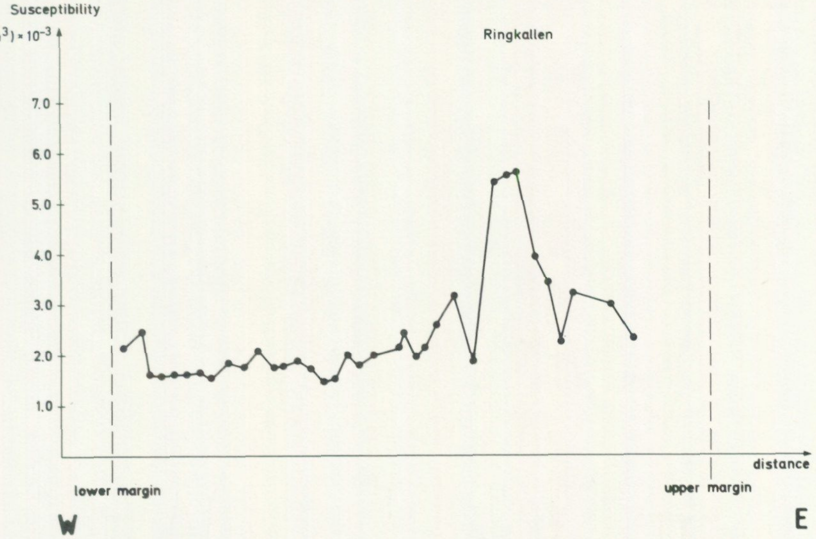

Fig. 34. *In-situ* susceptibility measurements across the dolerite sheet at Ringkallen. For position of profiles, see Figs. 1 and 3.

some of the trends in the whole-rock chemistry. These breaks occur at approximately 100 m from the lower contact (Larson 1980).

The susceptibility distribution at Rävsön is very similar to that of Ringkallen. However, the lower unit is somewhat thinner compared to Ringkallen and Edsätterfjärden. This might be a result of stratigraphical displacement caused by faulting, which probably occurred along a topographically distinct lineament; the sheet west of this lineament seems to be uplifted (Fig. 36). The An content of plagioclase together with the whole-rock chemistry show a distinct break at approximately the same position as reflected by the susceptibility pattern (Larson 1980). The susceptibility pattern and the rock-chemistry of the cross sheet profiles at Nordingrå shows that the multiple intrusion character of the sheet can be traced from the southern (Ringkallen) part to the northern (Rävsön) part of the peninsula (Fig. 2).

The susceptibility pattern across the dolerite sheet at Rypskär is similar to that at Ringkallen (Fig. 37). The sheet can thus be divided into a lower unit (about half the thickness of the sheet) with low and uniform susceptibility values (c. 2×10^{-3} cgs), and an upper unit with higher and more variable susceptibility. The lower magnetite enriched zone of the upper unit has susceptibility values of approximately 7×10^{-3} cgs. The two units coincide with the most distinct petrochemical zones as suggested by Larson (1980). The gravity profile across the sheet at Rypskär shows that faulting has not resulted in any drastic stratigraphical displacements of the 250 m thick dolerite sheet (Larson & Magnusson 1979).

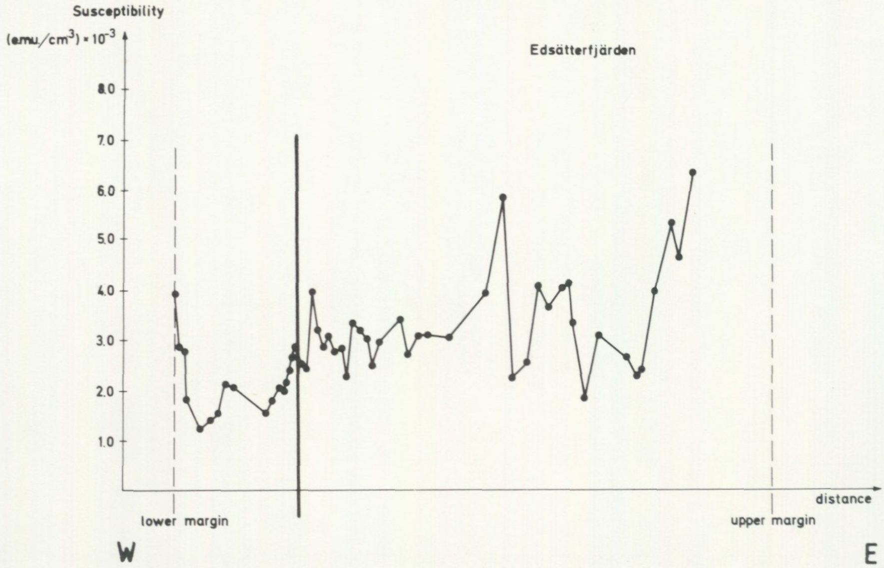

Fig. 35. *In-situ* susceptibility measurements across the dolerite sheet at Edsätterfjärden. Vertical line: topographical lineament. For position of profiles, see Figs 1 and 3.

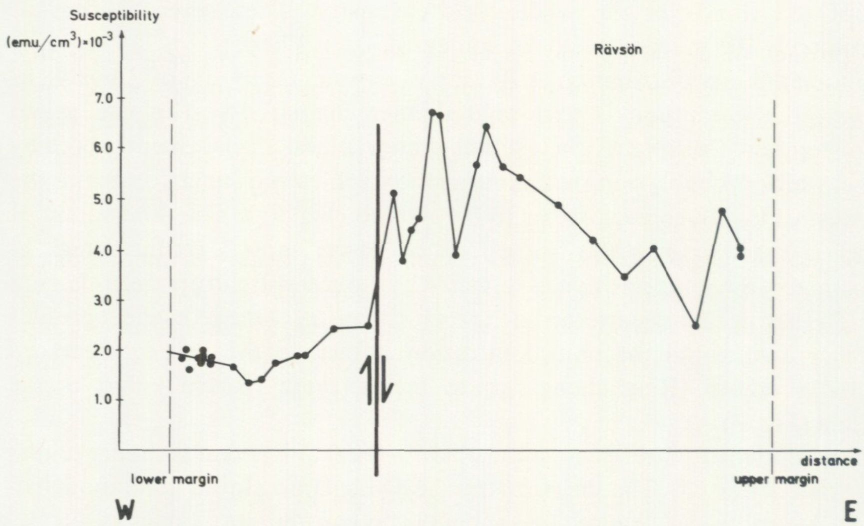

Fig. 36. *In-situ* susceptibility measurements across the dolerite sheet at Rävsön. Vertical line: topographical lineament, ⇅ : fault. For position of profiles, see Figs. 1 and 3.

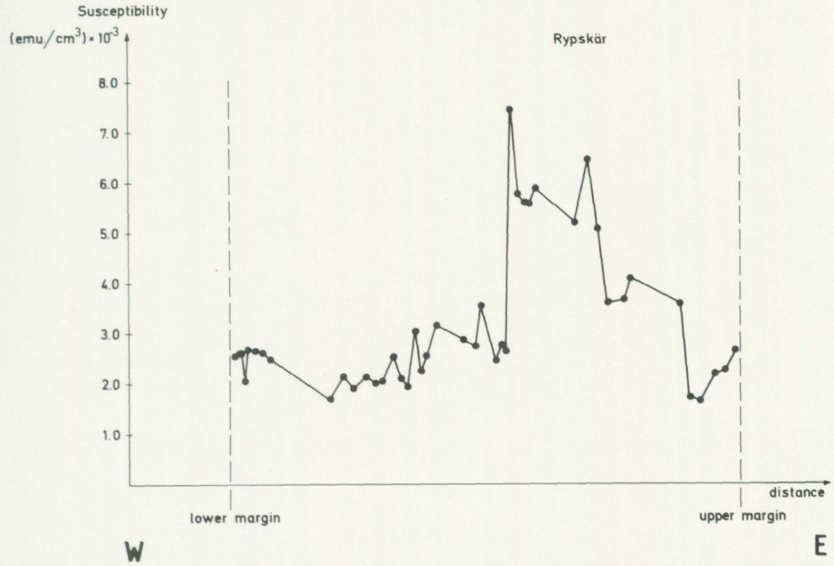

Fig. 37. *In-situ* susceptibility measurements across the dolerite sheet at Rypskär. For positon of profiles, see Fig. 1.

Two profiles (Häggdånger and Köpmanholmen) were measured across the large ring-shaped lopolithic intrusion (Fig. 1). They show no evidence of a multiple intrusion character in their susceptibility patterns (Figs. 38 and 39) which are rather uniform. The sheet has susceptibility values which are similar to those in the lower unit of the other profiles. However, the sheet has a slightly increasing susceptibility towards the upper margin.

Larson (1980) suggests that at least four different intrusions of ringlike shape (cf. Larson & Magnusson 1979) occur along the coast of the Province of Ångermanland. From petrochemical and geological evidence, he also considers that these intrusions are intimately related. The susceptibility measurements also support this hypothesis. These intrusions are characterized by the following susceptibility patterns.

1. The dolerite sheet characterizing the Ulvö Islands belongs to a dolerite intrusion which can be traced over the islands to the Skagsudde region (Fig. 1). The intrusion has a multiple character comprising a lower unit (c. 30 m thick) with low and uniform values of about 2×10^{-3} cgs, and a thicker upper unit (c. 220 m thick) with higher and more variable susceptibility. The lower part of the upper unit is very enriched in magnetite and has susceptibility values of $(12–29)\times10^{-3}$ cgs. These magnetite enriched horizons have been mined at several places on the Ulvö Islands.

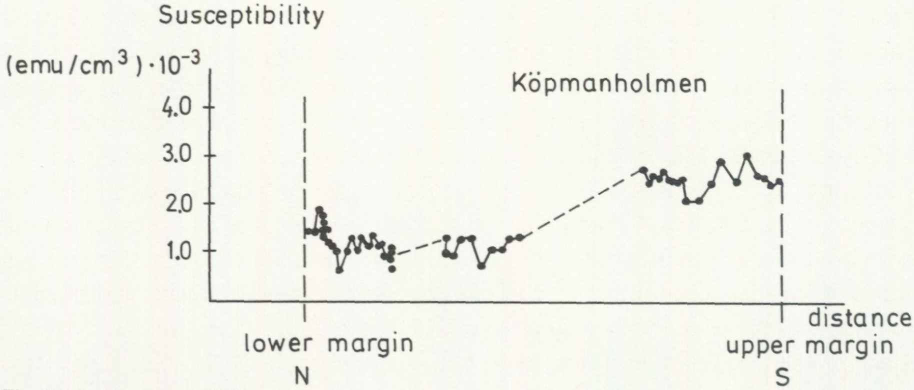

Fig. 38. *In-situ* susceptibility measurements across the dolerite sheet at Köpmanholmen. For position of profiles, see Fig. 1.

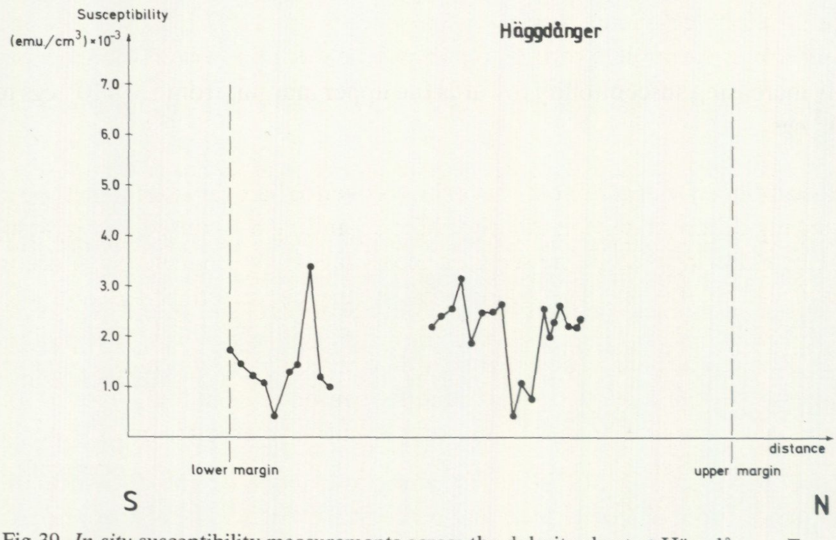

Fig.39. *In-situ* susceptibility measurements across the dolerite sheet at Häggdånger. For position of profiles, see Fig. 1.

2. Investigations of chemistry (Lundqvist & Samuelsson 1973;Larson 1980) and susceptibility patterns across the dolerite sheets indicate that the dolerite intrusion at Nordingrå is not the same as that which occurs on the Ulvö Islands. This dolerite probably belongs to a ring-formed intrusion which continues into the Bothnian sea south of the Ulvö Islands (Fig. 1). It also exhibits a multiple intrusion character with a lower unit (c. half the 250 m thick dolerite sheet) recording low and uniform susceptibility values of about 2×10^{-3} cgs, and an upper unit with a higher and more variable susceptibility. The lower magnetite enriched part of the upper unit has susceptibility values of about $(5–6)\times10^{-3}$ cgs.

3. The dolerite sheet at Rypskär has also a susceptibility pattern which differs from that of the Ulvö Islands. From the chemistry, Larson (1980) suggests that this sheet is not the same intrusion that can be traced from the Ulvö Islands to the Skagsudde region south of Rypskär (Fig. 1). The dolerite sheet at Rypskär therefore belongs to a roughly semicircular dolerite body outcropping north-east of Örnsköldsvik. This ring-formed dolerite sheet has a gentle inward dip (c. 20°) centering to a position east of Husum (Larson & Magnusson 1979). The susceptibility pattern is very similar to the pattern at Ringkallen, i.e., a lower unit with low and uniform susceptibility (2×10^{-3} cgs) and an upper unit with higher and more varying susceptibilities. The magnetite enriched zone at the lower part of the upper unit has susceptibility values similar to Ringkallen [i.e., $(5–7)\times10^{-3}$ cgs]. Each of the two units occupies about half of the sheet.

4. The large ring-shaped lopolithic intrusion outcropping between Köpmanholmen and Åvikebukten (Fig. 1) differs from the other intrusions by not having a multiple intrusion character. Instead, this sheet is characterized by a low and rather uniform susceptibility throughout the whole sheet. However, the sheet has a slightly increasing susceptibility towards the upper margin, from 1.0×10^{-3} cgs to 2.5×10^{-3} cgs.

The susceptibility measurements have thus proven to be a very useful method in distinguishing different units in dolerite sheets. Faulting has caused stratigraphical displacements in some of the sections across sheets, which have given rise to stratigraphical repetitions. The dolerite has a very characteristic susceptibility pattern across the sheet which can be used to trace stratigraphical repetitions in the sheet. By using a combination of gravity data and susceptibility measurements it is possible to evaluate the displacements caused by faulting. The *in-situ* susceptibility measurements have been a simple and fast method to investigate the character of dolerite sheets and is therefore very suitable as a pilot investigation for further chemical studies.

REFLECTANCE MICROSCOPY

The ferromagnetic minerals, which are responsible for the remanent magnetization and in most crystalline rocks also the main part of the induced magnetization (the dia- and paramagnetic minerals give an insignificant contribution to the induced magnetization), were studied using reflected light microscopy. However, if magnetite is only present in very minute amounts (<0.1 vol.%), the induced magnetization (susceptibility) is mainly carried by para- and diamagnetic minerals. In addition to the ferromagnetic minerals (i.e., pyrrhotite and magnetite) ilmenite and hematite have also been studied. The Fe-Ti oxide phases have also been studied and identified by scanning electron microscopy and qualitative elemental distributions obtained using Energy Dispersion. Results from the reflected light microscopy of the magnetic minerals in the Ulvö dolerite have been presented by Larson & Magnusson (1976) and will therefore not be presented in this study. The samples investigated in this study were selected from the observed trends in the susceptibility *versus* Q-ratio plots of the gabbro, anorthosite and sandstone (see Figs. 7, 9 and 13). The aim has been to clarify these observed trends.

NORDINGRÅ GABBRO

The dominating opaque phase in the gabbro is ilmenite, which occurs rather abundantly in all the studied polished sections. It generally occurs as irregular, larger grains of rodlike shape. Pyrrhotite occurs rather frequently as discrete anhedral grains or in grains which consist of co-existing ilmenite and pyrrhotite; pyrrhotite also occurs sparsely as subhedral or euhedral grains.

Magnetite generally occurs sporadically as discrete larger anhedral homogeneous grains without exsolution textures. Only in very few magnetites with ilmenite lamellae have been observed orientated along the octahedral planes of magnetite; lamellar ilmenite intergrowths are therefore practically absent in the magnetites. Exsolved oxides exhibiting myrmekitic textures (Fig. 40) occur rather infrequently in some of the polished sections. These exsolved oxides usually consist of both ilmenite and magnetite. In general, fine-grained exsolved oxides only occur in insignificant amounts in the studied sections. Magnetite and pyrrhotite occur rather abundantly in the serpentinized parts of the silicates where they are characterized by irregular and anhedral shapes. In most of the studied thin sections serpentinization occurs mainly along cracks in olivine; other sections are characterized by fresh silicates devoid of any recognizable serpentinization.

The magnetic grains (magnetite and pyrrhotite) usually have grain sizes larger than 50μm and are therefore responsible for magnetization of the multidomain type. The magnetites contributing to the fine myrmekitic textures, and the small percentage of magnetites which have been divided into smaller units by lamellar intergrowths with ilmenite, are the only observed examples which might have such small grain sizes that they can carry magnetization of single or pseudo-single domain type. Because these fine-grained magnetites only occur in minor amounts, the gabbro has a very insignificant component of high coercive remanent magnetization. The gabbro is therefore characterized by having a small proportion of remanent magnetization (low Q-values) and a soft and easily demagnetized remanent magnetization. Thus, the main part of the magnetization is carried by magnetic grains of multidomain type.

Samples for study were also taken along the observed trend representing decreasing susceptibility with increasing Q-ratio (Fig. 7).

Fig. 40. Gabbro specimen showing exsolved oxides (light areas) with myrmekitic textures. These stringlike oxides consist of both ilmenite and magnetite. Reflected light under oil. X-nicols; 500×.

The two sections from the samples with low susceptibility values in the paramagnetic region ($<10^{-4}$ cgs) were fresh and showed no visible serpentinization. The section from the sample with the highest susceptibility showed the strongest serpentinization; in this case some olivine grains were completely altered (Fig.41). The sections from the gabbro with more moderate susceptibility show a lesser degree of serpentinization, mostly confined to cracks in the olivine. Increasing susceptibility is therefore generally connected with a progressively increasing serpentinization of the samples. Apart from the serpentinized parts, the gabbro has a very low content of ferromagnetic minerals and therefore has susceptibility values in the paramagnetic region. The greatest percentage of ferromagnetic minerals therefore occurs in the serpentinized parts of the gabbro.

The decrease in Q-ratio with increasing susceptibility is probably due to the increasing amount of large multidomain grains in serpentinized silicates. An increased proportion of induced magnetization will therefore be carried by

Fig. 41. Serpentinized gabbro containing some strongly altered olivine grains (dark areas). Plane polarized light; 50×.

multidomain grains in comparison with the submicroscopic ferromagnetic impurities in the paramagnetic minerals, or, by smaller grains with a magnetization of the single and pseudosingle domain type. These smaller grains contribute more to the remanent magnetization than the susceptibility. However, two sections from samples with low magnetization in the paramagnetic region have neither myrmekitic textures nor magnetite grains with ilmenite lamellae. The main part of the remanent magnetization therefore appears to be carried by the submicroscopic ferromagnetic impurities in the paramagnetic minerals. The trend of increasing susceptibility with increasing Q-ration in the paramagnetic region (Fig. 7) is probably caused by an increasing amount of these impurities.

NORDINGRÅ ANORTHOSITE

The dominating opaque phase in the anorthosite is ilmenite which is rather abundant and usually occurs as large irregular anhedral grains. In some of the ilmenite grains, exsolved hematite is present in the form of small irregular blebs and lamellae and occurs also along the grain boundaries of the ilmenite. In some of the pyroxene grains, exsolved hematite occurs parallel to the cleavage planes.

Some plagioclase crystals contain numerous dispersed, very fine, needle-shaped Fe-Ti-oxide microlites exsolved along the cleavage planes of the plagioclase (Fig. 42). The smaller microlites restricted to one lamella are usually of pure Fe-oxide, whilst the larger microlites which traverse several lamellae, usually consist of ilmenite. The small size precludes positive identification of the Fe-oxides, however, some of these are probably magnetite.

Magnetite is generally present as large anhedral grains, but in some biotites and amphiboles smaller euhedral magnetite grains of octahedral shape occur. The anhedral magnetite grains occur both as homogeneous grains devoid of exsolution textures, and as grains characterized by intergrowths of ilmenite lamellae along the octahedral planes. The grains with the ilmenite lamellae usually occur in contact with ilmenite grains. The intergrowth patterns of magnetite and ilmenite are usually on a very fine scale, visible only at very high magnifications ($>1\,000\times$) under oil (Fig. 43). Pyrrhotite, which can be euhedral, subhedral or anhedral in form, generally occurs rather sparsely except for one section.

The magnetite which occurs as very fine exsolved microlites in the plagioclase crystals, will, due to their small grain sizes, carry a hard remanent magnetization of single to pseudo-single domain type. Furthermore, within the ilmenomagnetite grains, because the ilmenite lamellae subdivide the magnetite into very small units, these magnetites will also carry a similar remanent magnetization. The other magnetites, which typically occur as large homogeneous grains lacking exsolution textures, carry a magnetization of multidomain type. These multidomain grains result in a small contribution to the remanent magnetization but a large contribution to the susceptibility. The small magnetite grains which carry magnetization of single and pseudo-single domain type will, on the other hand, mainly contribute to the remanent magnetization and result in a small contribution to the susceptibility. The remanent magnetization is therefore mainly carried by the magnetite segments coexisting with the ilmenite lamellae and by the fine exsolved magnetites in the plagioclase crystals. The remanent magnetization of the anorthosite is therefore characterized by a hard remanent magnetization with rather high coercivities. AC-demagnetization also shows that soft remanent magnetization constitutes an insignificant proportion of the remanent magnetization.

The samples with low susceptibilities in the paramagnetic region ($<10^{-4}$ cgs) show a large scatter in Q-ratios from 0.1 to 30 (Fig. 9). Investigated sections were

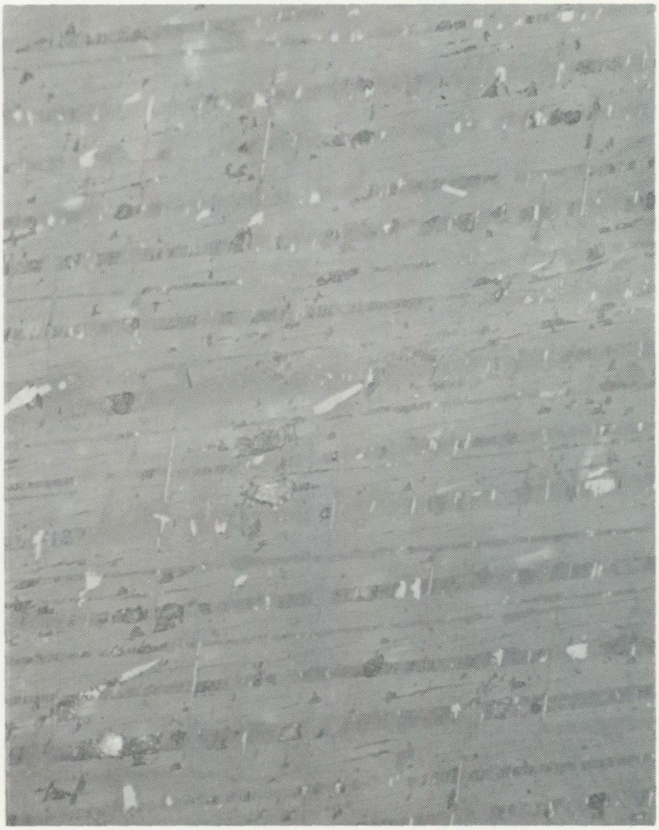

Fig. 42. Needle-shaped Fe-Ti-oxide microlites (light areas) exsolved along the cleavage planes of a plagioclase in anorthosite. Reflected light. X-nicols; 500×.

selected from samples representing this scatter. Except for one section, in which large anhedral ilmenite grains occur rather frequently, all samples from the paramagnetic region are characterized by a very low content of opaque phases. In contrast to samples with low Q-ratios, samples with a high Q-ratio generally have a greater content of magnetite coexisting with ilmenite lamellae and as exsolution phases in plagioclase. The very high Q-ratios and low susceptibilities of some of the samples are therefore due to the fact that the dominating magnetic minerals in these samples are fine-grained magnetites of single and pseudo-single domain type, while larger magnetites of multidomain type are practically absent. Thus, the scatter probably is an effect of various amounts of these small magnetite grains. Increasing susceptibility generally indicates higher contents of opaque phases in the samples. In addition, magnetite also occurs more frequently in the form of larger homogeneous magnetite grains of multidomain type, and also coexisting with ilmenite lamellae or as exsolved magnetite in plagioclase.

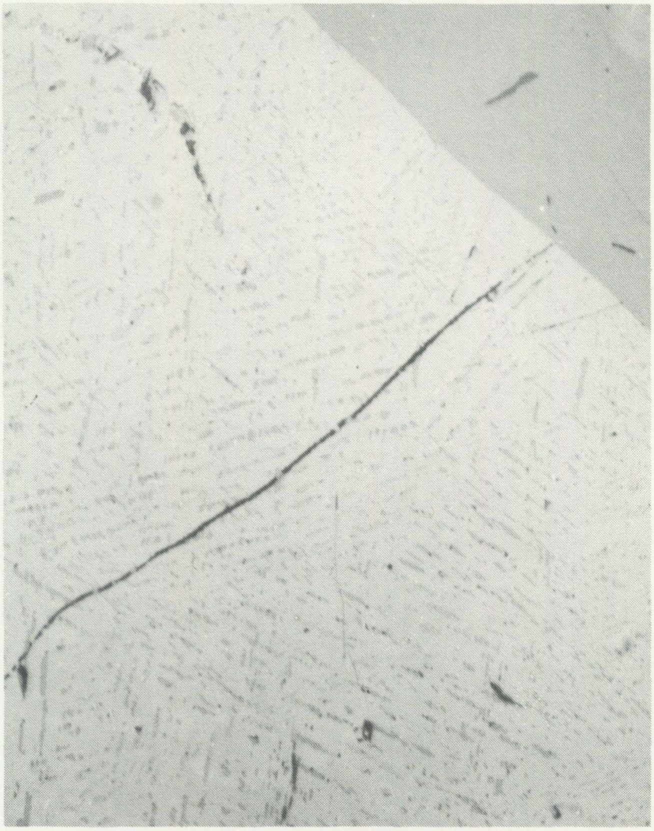

Fig 43. Anorthosite specimen showing magnetite with intergrowths of ilmenite (darker areas) orientated along the octahedral planes. Reflected light under oil. X-nicols; 1040×.

The observed trend of decreasing Q-ratios with increasing susceptibility (Fig. 9) is therefore probably due to an increasing proportion of larger grains of multidomain type, which contribute significantly to the susceptibility and less significantly to remanent magnetization.

The anorthosite is characterized by two areas with different susceptibilities, that is, an area with a low susceptibility of paramagnetic magnitude at the western margin of the anorthosite outcrop and an area with a higher susceptibility of ferromagnetic magnitude at the eastern part of the Nordingrå area (Fig. 2). Also, according to G. Lundqvist (1972), the eastern area has a somewhat higher average Fe_2O_3 content but a similar FeO content ($Fe_2O_3 = 1.32 \pm 0.61\%$; $FeO = 4.6 \pm 1.5\%$) compared with the western margin ($Fe_2O_3 = 0.61 \pm 0.37\%$; $FeO = 4.2 \pm 1.8\%$).

The sections investigated from the western margin have very few larger magnetite or pyrrhotite grains which carry magnetization of the multidomain type. They therefore have a susceptibility of paramagnetic magnitude. These samples also show a larger scatter in the Q-ratios from 1 to 10 (Fig. 9). The sections from the samples with a low Q-ratio also contain very few grains which carry magnetization of a single- and pseudosingle domain type, i.e., magnetite coexisting with ilmenite lamellae or as an exsolved phase in plagioclase. Thus, magnetite and pyrrhotite generally occur very rarely in this part of the anorthosite.

The samples from the eastern part of the peninsula fall along the ferromagnetic trend of increasing susceptibility with decreasing Q-ratio (Fig. 9). This corresponds to an increased content of large magnetite grains which carry magnetization of the multidomain type. Samples with a low susceptibility have high Q-ratios and contain very few larger grains of the multidomain type. However, magnetite occurs as a phase coexisting with ilmenite lamellae and as an exsolved phase in plagioclase, and therefore carries magnetization of single- or pseudosingle domain type. Thus, magnetite occurs more abundantly in the eastern area.

JOTNIAN SANDSTONE

Investigated sections indicate very minute amounts of opaque phases; the dominating opaque phase is hematite. It generally occurs as very fine-grained clusters which occur together with poorly crystallized iron hydroxide (limonite). These aggregates are generally present in the feldspars or occur interstitially to the feldspars and quartz. Hematite also occurs sparsely as larger anhedral grains and in aggregates composed of larger grains.

Only very few ilmenite and magnetite grains have been observed in some of the sections. The magnetite occurs in rather small euhedral grains of octahedral shape. One of the sections has been collected from a regolith consisting of *in-situ* material derived partly from the sub-Jotnian complex and partly from the Svecokarelian rocks (Bergman 1980). This sample is composed mainly of sericitized plagioclases; the opaque phases, which mostly form large anhedral grains, occur rather abundantly in the chloritized parts. Most common of these are ilmenite with subordinate magnetite.

The susceptibility of the samples indicates that magnetite occurs very infrequently, a fact supported by the minute amounts of opaque phases. The thermal demagnetization and alternating magnetic field demagnetization (the coercivity spectra of the remanent magnetization) show that the remanent magnetization is carried by very fine-grained magnetites which are virtually submicroscopic in size. These probably occur together with the fine-grained hematite aggregates. The very low content of magnetites and the small sizes of these grains (which carry the remanent magnetization) preclude positive identification by reflectance microscopy.

The plot of the sample susceptibility *versus* Q-ratio indicates a decreasing Q-ratio with increasing susceptibility; the samples selected for microscopy were taken along this trend (Fig. 13). In sections representing the lowest susceptibilities, larger oxide grains are practically absent. However, these sections, as well as the remainders, have fine, almost submicroscopic aggregates of hematite. The oxides generally occur more frequently in samples which have high susceptibilities in comparison with samples having low susceptibilities (for example, the section from the regolith has the highest susceptibility of all samples). Although most of the observed larger oxide grains are hematites, the sections in which oxides occur more frequently probably also have a somewhat higher content of larger euhedral magnetites. These multidomain magnetite grains (<50 μm) contribute essentially to the susceptibility but also a little to the remanent magnetization. Decreasing Q-ratios with increasing susceptibility might therefore be caused by an increasing amount of these larger magnetite grains as compared with the very fine-grained magnetites which carry the rather hard remanent magnetization.

PALAEOMAGNETIC POLE POSITIONS

The collected samples of the gabbro, anorthosite and Jotnian sandstone were AC-demagnetized in order to investigate the pole position of these rocks. The pole position of the collected samples from the Ulvö dolerite have already been presented in Larson & Magnusson (1976) and Magnusson & Larson (1977). The samples were demagnetized by a cleaning treatment of the samples in a stepwise increased alternating magnetic field. After each demagnetization step, the remanent magnetization of the samples was measured with a spinner magnetometer.

NORDINGRÅ GABBRO

In all, 27 samples of the gabbro were demagnetized. Two pilot samples were demagnetized by using steps of 50 Oe witin the range of 50 Oe to 2 000 Oe peak fields. This enabled the stability of the directions and the coercivity spectra of the remanent magnetization to be investigated. The other samples were demagnetized in 100, 200, 300, and 500 Oe peak fields and three of these samples were also demagnetized in 600, 800, 1 000, 1 200, 1 600, and 2 000 Oe peak fields. The gabbro is characterized by a soft remanent magnetization where more than 80% of the remanent magnetization was removed after demagnetization in a 100 Oe peak field (see Fig. 44). This is in agreement with the reflectance microscopy, where the observed magnetic minerals (magnetite and pyrrhotite) occur as larger grains, which carry magnetization of multidomain type.

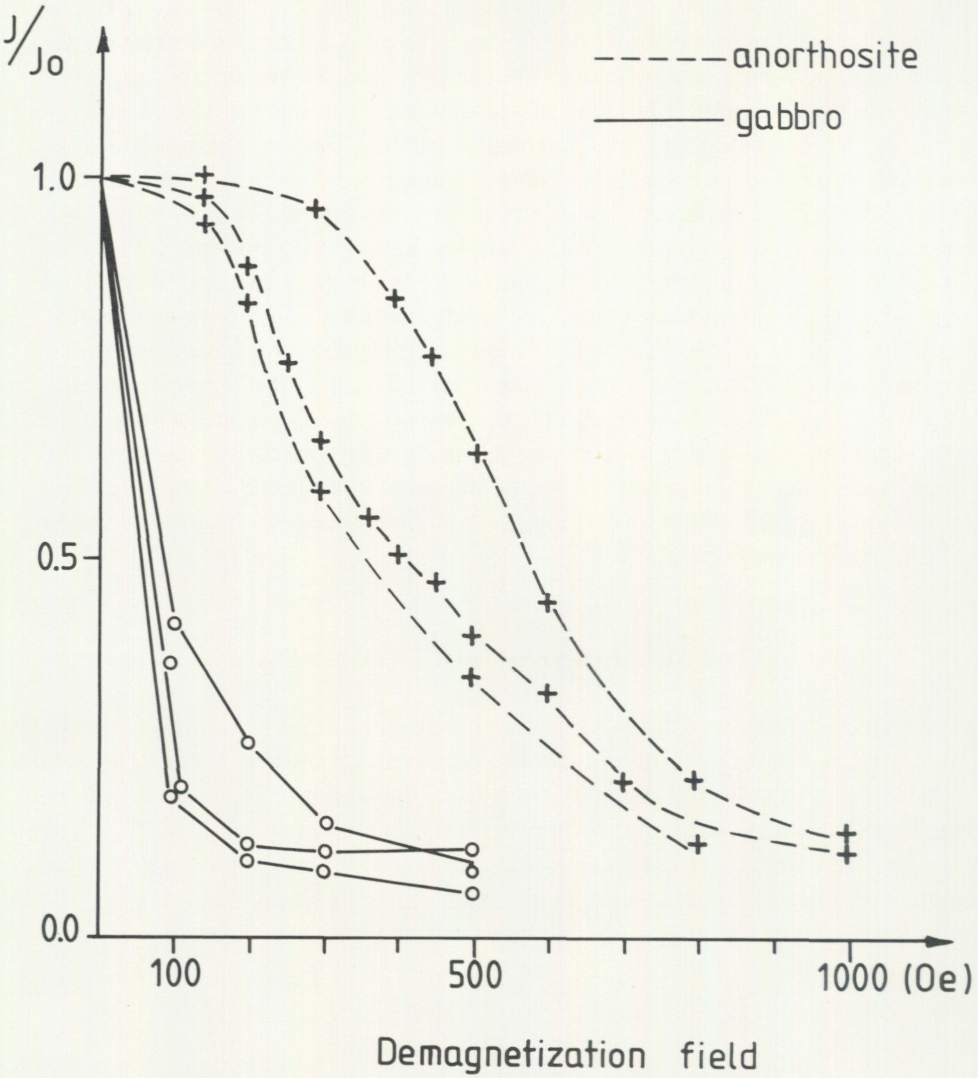

Fig. 44. Six examples of progressive alternating magnetic field demagnetization of the gabbro and anorthosite. Intensity of magnetization is expressed as a fraction of the initial natural remanent magnetization (Jo).

The remanent magnetization of the samples showed an unstable direction of magnetization under the progressive cleaning treatment in the alternating magnetic fields. The directions of the remanent magnetization also showed a high scatter after cleaning in the different alternating magnetic fields. It has therefore not been possible to establish any palaeomagnetic pole position for the gabbro.

However, in some samples from the Nordingrå gabbro, Piper (1980) has been able to isolate a component of remanent magnetization with very high coercivity

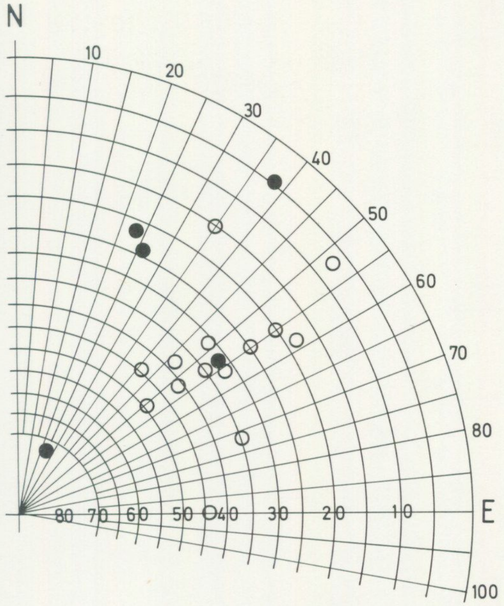

Fig. 45. Directions of natural remanent magnetization in the anorthosite plotted on a stereographic projection. Open circle: negative inclination. Filled circle: positive inclination.

and a stable direction of magnetization. The stable component of remanent magnetization has coercivities in excess of 1 600 Oe. Thermal treatment of the samples above the Curie temperature of magnetite shows a very small component of remanent magnetization with a stable direction which corresponds to the high coercive component. This component is lost at the Curie temperature of hematite, which indicates that the stable high coercive component is a parasitic ferromagnetic magnetization in the hematite (Piper 1980). The pole position of the high coercive component established by Piper (1980) is 138.1° E, 36.9° N.

NORDINGRÅ ANORTHOSITE

In all, 20 samples of the anorthosite were demagnetized using a similar approach to that outlined for the gabbro. The anorthosite has a rather hard remanent magnetization, where most of the samples have more than 50% of the remanent magnetization left after treatment in a 300 Oe peak field (see Fig. 44). This rather hard remanent magnetization is carried by magnetites present as fine intergrowths with ilmenite lamellae and by fine needle-shaped exsolved magnetite microlites in the plagioclase crystals.

The natural remanent magnetization of the samples are fairly well concentrated in a direction which differs markedly from the present geomagnetic field (Fig. 45).

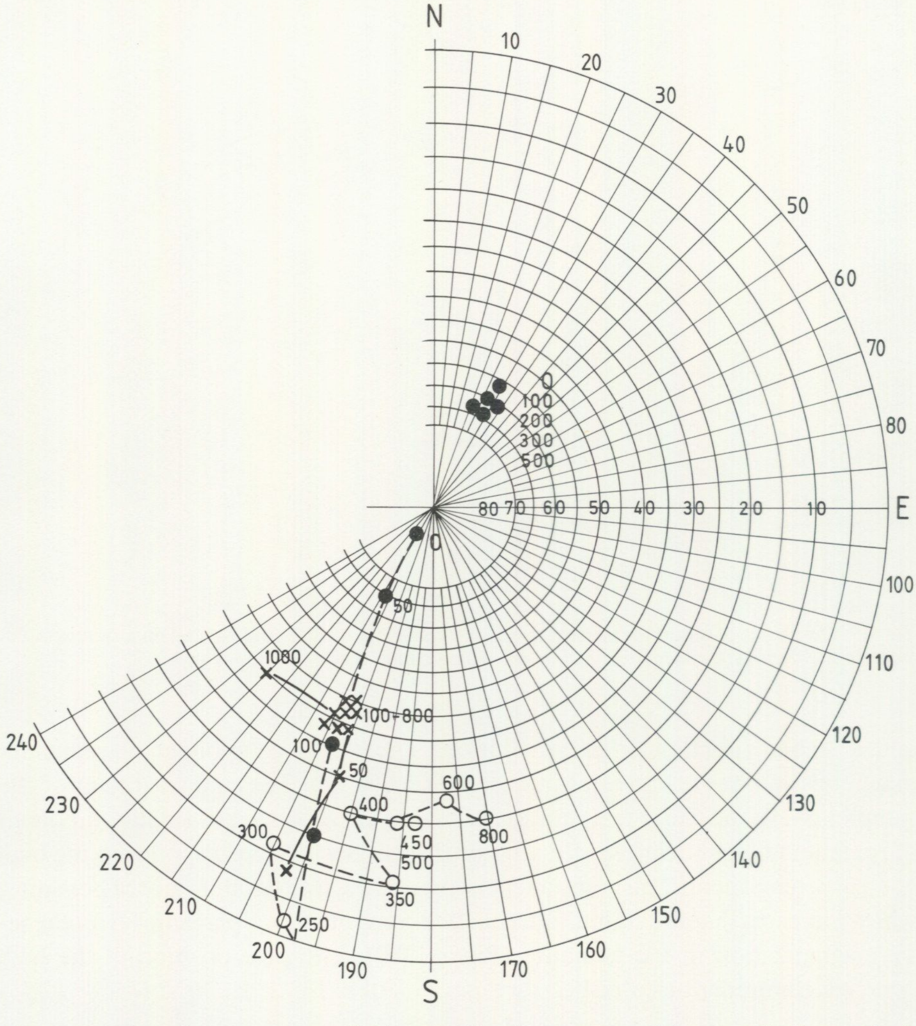

Fig. 46. Direction of remanent magnetization after cleaning treatment of three anorthosite samples in alternating magnetic fields. Symbols as in Fig. 45. × and ○: negative inclination. These three samples have a direction of remanent magnetization unrelated to the dolerite sheet.

The directions are only slightly influenced by treatment in the alternating magnetic fields, indicating a small contribution of viscous remanent magnetization (Fig. 47). After removing a small soft component, the smallest scatter in the directions of the remanent magnetization was achieved after treatment of the samples in 200 Oe peak fields. Treatment in higher peak fields than 500 Oe gives an increasing scatter of the directions of the remanent magnetization. The mean direction of the remanent magnetization for the 9 sites is D = 47.5°, I = –32.1° (α 95 = 7.5°). This direction is not significantly different from the mean direction of the post-Jotnian Ulvö dolerites, where extensive studies have been carried out

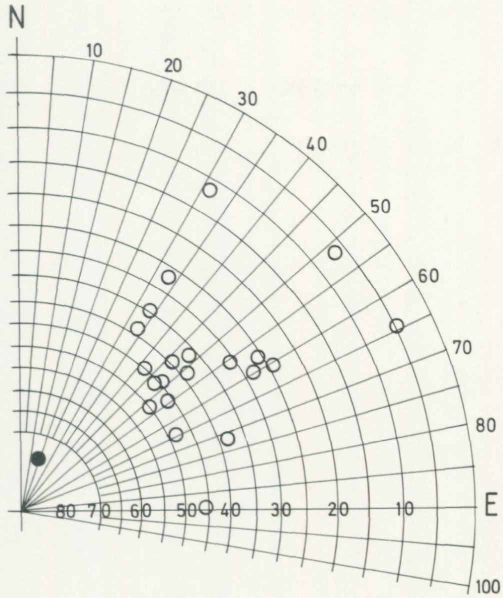

Fig. 47. Directions of remanent magnetization after treatment of anorthosite samples in 200 Oe peak field. Symbols as in Fig. 45.

by Larson & Magnusson (1976), Poorter (1976), Magnusson & Larson (1977), and Piper (1979). The mean direction calculated from all these investigations is D = 47.5°, I = -45.7°. It therefore appears that the thermal effect of the dolerite has been sufficient to accomplish an extensive remagnetization of the adjoining anorthosite. A palaeomagnetic study by Piper (1980) also reports an extensive remagnetization of the gabbro-anorthosite complex, where all sites east of the dolerite possess a very stable remanent magnetization with a direction similar to that of the dolerite. These sites are situated above the gently (5°–25°) eastward dipping dolerite sheet.

The sites close to the western margin of the dolerite also possess a post-Jotnian direction of magnetization. Even so, Piper (1980) was able to isolate a direction similar to that of the gabbro in anorthosite samples from four sites at the western margin of the dolerite by thermal treatment of the samples in temperatures above the Curie temperature of magnetite. This component of magnetization is probably carried by hematite which has a parasitic ferromagnetism.

Three of Piper's (1980) investigated sites, situated at a larger distance from the western margin of the dolerite, have magnetizations unrelated to that of the dolerites. Most of these sites have a north-east positive or a south-west negative direction, which is the direction found in the gabbro. With thermal treatment these directions change little up to the Curie point of hematite. In this study, these

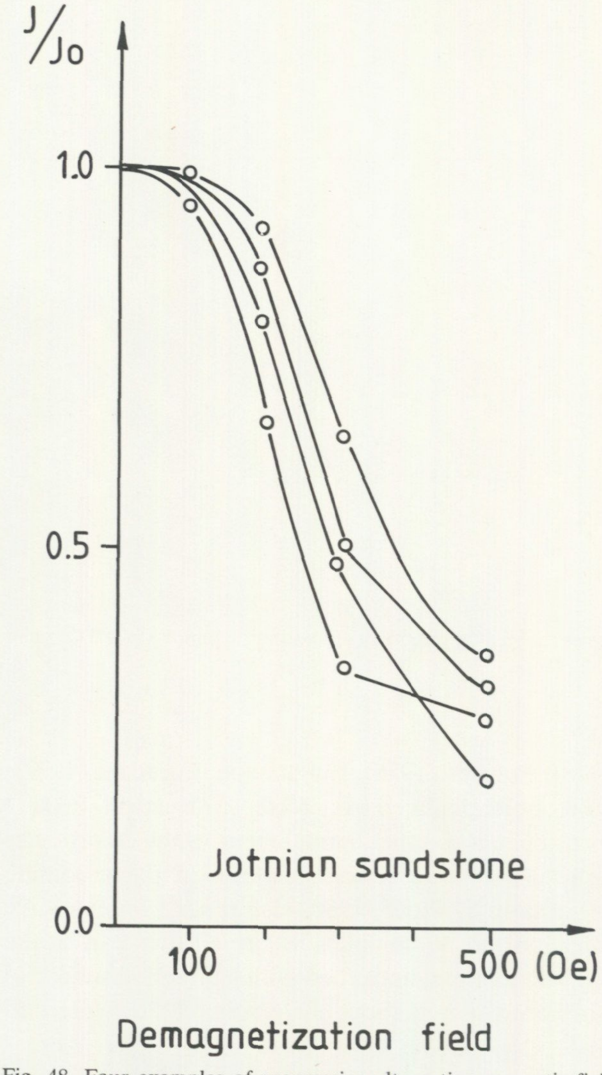

Fig. 48. Four examples of progressive alternating magnetic field demagnetization of the Jotnian sandstone. Intensity of magnetization is expressed as a fraction of the initial natural remanent magnetization (Jo).

directions were also found in 4 samples which were collected at the westernmost part of the anorthosite area (see sites marked by arrows in Fig. 5). After removing a small soft component by treatment in 50 to 150 Oe peak fields, the directions were stable up to treatment in 1000 Oe peak fields (see Fig. 46). The pole position for the gabbro-anorthosite complex without post-Jotnian remagnetization is 138.1° E, 36.9° N (Piper 1980).

TABLE 1. Jotnian sandstones in eastern part of central Sweden; site mean palaeomagnetic statistics after alternating field cleaning.

Site No.	N	D	I	K	α_{95}	palaeomagnetic pole position
1	2	53.1	– 7.2	14.6	40.8	
2	6	48.4	–17.4	28.9	13.6	
3	4	49.4	–43.0	61.0	11.8	
4	3	62.6	–46.5	6.8	51.3	
5	3	39.4	–32.7	26.7	24.3	
6	2	56.0	–30.8	75.2	29.1	
7	6	37.8	–40.7	24.3	13.8	
Combined mean direction of sites 1 and 2						
		50.8	–12.3	105.1	24.6	146.7°E, 10.9°N
Combined mean direction of sites 3, 4, 5, and 7						
		48.8	–39.1	58.8	10.1	154.2°E, 3.2°S
Combined mean direction of all sites						
		49.4	–31.5	25.8	12.1	151.8°E, 1.3°N

JOTNIAN SANDSTONE

In all, 27 samples from 7 sites were demagnetized. Five pilot samples were demagnetized by using steps of 100 Oe from 100 to 2 000 Oe peak fields. The rest of the samples were demagnetized in 100, 200, 300, and 500 Oe peak fields. The sandstone has a rather hard remanent magnetization, where most of the samples have more than 60% of the magnetization left after treatment in a 300 Oe peak field (Fig. 48). This rather hard remanent magnetization is carried by very small fine-grained magnetites which probably occur together with the fine-grained hematite aggregates.

The direction of remanent magnetization is only slightly influenced by treatment in alternating magnetic fields. The site mean value of the natural remanent magnetization and the remanent magnetization remaining after cleaning by alternating field treatment show very similar directions of magnetization (Figs. 49 and 50). The smallest scatter in these directions is achieved after treatment of the samples in a 200 Oe peak field. The site mean palaeomagnetic statistics after treatment by alternating field demagnetization are shown in Table 1. After treatment in a field stronger than 500 Oe, there is an increasing scatter of the remanent magnetization.

Five of the sites have directions which are very similar to the Jotnian dolerite ($D = 47.8°$, $I = -45.5°$). The combined mean value of these sites is $D = 48.8°$ and $I = -39.1°$. The similarity might be due to the fact that the dolerite has accomplished a remagnetization of the Jotnian sandstone. This suggestion is also strengthened by the fact that the dolerite has accomplished an extensive remagnetization in the

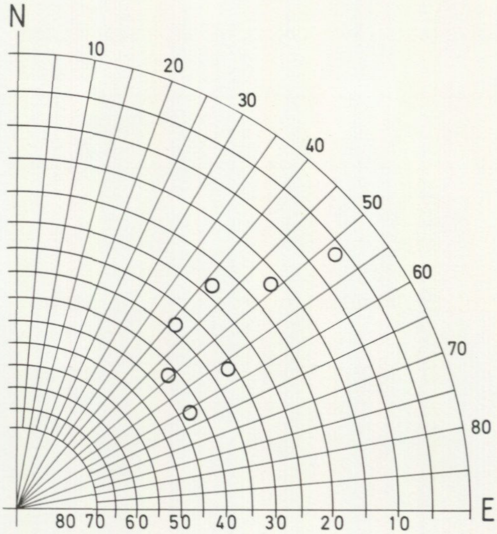

Fig. 49. Stereographic plot of all site mean directions of the natural remanent magnetization in Jotnian sandstone. Symbols as in Fig. 45.

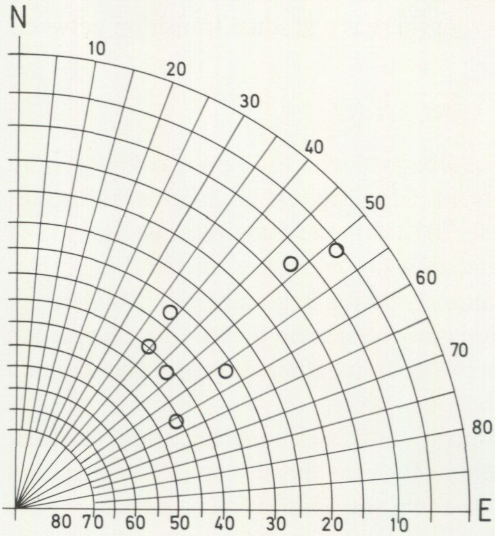

Fig. 50. Stereographic plot of all site mean directions of remanent magnetization after cleaning the Jotnian sandstone samples by alternating magnetic fields. Symbols as in Fig. 45.

gabbro-anorthosite massif. The other two sites have somewhat lower inclinations of D = 53.1°, I = −7.2° and D = 48.4°, I = −17.4°. At the investigated sites there is no tendency towards different inclinations or declinations with increasing distance to the overlying dolerite contact. No explanation for the anomalously low inclination at some of the sites has been found. The palaeomagnetic pole positions for the combined five and seven sites are (154.2° E and 3.2° S) and (151.8° E and 1.3° N), respectively. These pole positions are rather similar to the pole position of the Jotnian sandstone in Satakunta, south-western Finland, which is 180° E and 3° N (Neuvonen 1973).

CONCLUSIONS

The gabbro is characterized by low intensities of magnetization of paramagnetic magnitude ($<2 \times 10^{-4}$ cgs) or just above this region. This can be explained by the general lack of ferromagnetic minerals except for those contained within the serpentinized silicates, represented mainly by olivine, where magnetite and pyrrhotite occur rather abundantly. Higher and increasing susceptibility values in the gabbro are therefore connected to a progressively increasing serpentinization of the gabbro. Extensive *in-situ* susceptibility measurements across the gabbro-anorthosite massif show that the gabbro has a very uniform intensity of magnetization throughout the whole massif. This indicates that a simple and uniform rockforming process has been acting on the minerals containing iron. The other measured petrophysical properties (density and Q-ratio) of the gabbro also show simple monomodal frequency distributions. The gabbro therefore appears to be rather homogeneous body. However, the gabbro has a zone characterized by a decreasing amount of paramagnetic minerals towards the contact between gabbro and anorthosite. This indicates that there is a gradual transition between the two rocks.

The anorthosite shows more complex frequency distributions of the measured petrophysical properties. However, both the frequency distributions of the density and the Q-ratio can be approximated by distributions of the monomodal type. The *in-situ* susceptibility measurements across the gabbro-anorthosite massif show that the anorthosite has two separate areas with different intensity of magnetization. The area to the west of the dolerite sheet has very low susceptibilities of paramagnetic magnitude. Both the gabbro and the anorthosite west of the dolerite sheet are therefore characterized by a very low intensity of magnetization. The area east of the dolerite, which mainly consists of anorthosite, has about 10 times higher susceptibility values compared to the anorthosite west of the dolerite sheet. However, the eastern part of the area west of the dolerite sheet shows an eastward increasing susceptibility. This indicates a gradual transition between the two units with different susceptibility. This in turn suggests that the anorthosites in the two areas might have crystallized at different depths (i.e., at different stratigraphical positions) or belong to different phases of intrusion. In addition, the anorthosite west of the dolerite sheet has more complex and multimodal frequency distributions of the susceptibility values, which indicates more complex rock-forming processes acting on the minerals containing iron.

The Jotnian sandstone is characterized by very low magnetizations which are about 10 times weaker than the magnetization of paramagnetic minerals. Therefore magnetite must occur in very minute amounts in the Jotnian sandstone. However, alternating magnetic field and temperature demagnetization measurements show that the remanent magnetization is carried by fine-grained magnetites which are almost submicroscopic in size.

The multiple intrusion character of the Ulvö dolerite sheets, established by Lundqvist & Samuelsson (1973) and by Larson (1980), is also evident from the different magnetic characters of the multiples. Apart from the large ring-shaped lopolithic intrusion outcropping between Köpmanholmen and Åvikebukten, which has similar susceptibility values across the whole sheet, the dolerite sheets are characterized by a lower unit with low uniform susceptibility and an upper unit with higher and more varying susceptibility values. The results indicate that at least four different dolerite sheets occur along the coast of Ångermanland.

The plots of the sample susceptibility *versus* Q-ratio show that the investigated rocks have characteristic trends. The gabbro shows a trend of increasing susceptibility with increasing Q-ratio in the paramagnetic region. This trend might be due to an increasing amount of ferromagnetic impurities in the paramagnetic minerals. In the ferromagnetic region the gabbro shows a trend of increasing susceptibility with decreasing Q-ratio. This is probably caused by an increasing amount of larger multidomain grains in the serpentinized parts, which essentially contribute to the susceptibility, in comparison to the smaller grains which give a larger contribution to the remanent magnetization (for example the small ferromagnetic impurities in the paramagnetic minerals).

The anorthosite and the Jotnian sandstone show an increasing susceptibility with decreasing Q-ratio. These trends are probably due to an increasing proportion of larger multidomain grains in comparison to smaller magnetite grains which carry magnetizations of single or pseudo-single domain type. The anorthosite samples with susceptibility values in the paramagnetic region, where large multidomain grains are practically absent, show a great scatter in the Q-ratios (which vary between 0.1 and 4.0). This is caused by different amounts of fine magnetite grains which carry magnetizations of single or pseudo-single domain type (exsolved magnetites in feldspars and magnetites with fine networks of ilmenite lamellae). Increased amounts of these grains contribute essentially to the remanent magnetization and very little to the susceptibility, i.e., they increases the Q-ratio.

The dolerite intrusion has accomplished an extensive remagnetization of the adjoining gabbro-anorthosite massif and has therefore reset the remanent magnetization in a direction similar to that of the Ulvö dolerite. Because the Jotnian sandstone also exhibits a direction similar to that of the Ulvö dolerite, the latter has therefore probably also reset the remanent magnetization in the sandstone.

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