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AND
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THE MAGNETIC AND
CHEMICAL CHARACTER OF
Fe-Ti OXIDES
IN THE ULVÖ DOLERITE,
CENTRAL SWEDEN



STOCKHOLM 1976

SVERIGES GEOLOGISKA UNDERSÖKNING

SERIE C NR 723

AVHANDLINGAR OCH UPPSATSER

ÅRSBOK 70 NR 5

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ISBN 91-7158-106-5

Kartan på s. 8 är godkänd från sekretessynpunkt för spridning.
Statens lantmäteriverk 1976-11-19

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C DAVIDSONS BOKTRYCKERI AB, VÄXJÖ 1976

CONTENTS

Abstract	3
Introduction	3
The Fe-Ti oxides	6
X-Ray measurements	7
Susceptibility and natural remanent magnetization (NRM)	8
AC-demagnetization	11
Temperature demagnetization	13
Curie-point measurements	15
Palaeomagnetic pole position	18
Conclusions	22
Acknowledgements	24
Tables	25
References	28

ABSTRACT

A layered dolerite sheet in the archipelago of Ångermanland, central Sweden, has been investigated with respect to its susceptibility, natural remanence and its opaque mineralogy. The palaeomagnetic pole position has been determined by AC-demagnetization. The proportion of ulvite to magnetite has been determined by means of temperature demagnetization. The Ti-content of the magnetite-ulvite_{ss} series has been determined by X-ray and Curie-point measurements and by temperature demagnetization.

INTRODUCTION

The purpose of this investigation is to clarify the magnetic and chemical character of Fe-Ti oxides in the Ulvö dolerite. This rock belongs to a larger dolerite province in central Sweden. (Fig. 1.) These rocks, which are common in the counties of Kopparberg, Gävleborg, Jämtland and Västernorrland are considered to be of Jotnian Age (Magnusson et al. 1960). Dolerites of Jotnian Age are also found further south in central Sweden. A dolerite from the investigated area has recently been dated by K/Ar-method (Welin and Lundqvist 1975) the result being 1245 ± 20 m.y.

The petrology of the area has been investigated by Lundbohm (1899) and Sobral (1913). A chemical investigation of the Ulvö dolerite was carried out by Lundqvist and Samuelsson (1973) at Ringkallen hill. In some areas dolerites

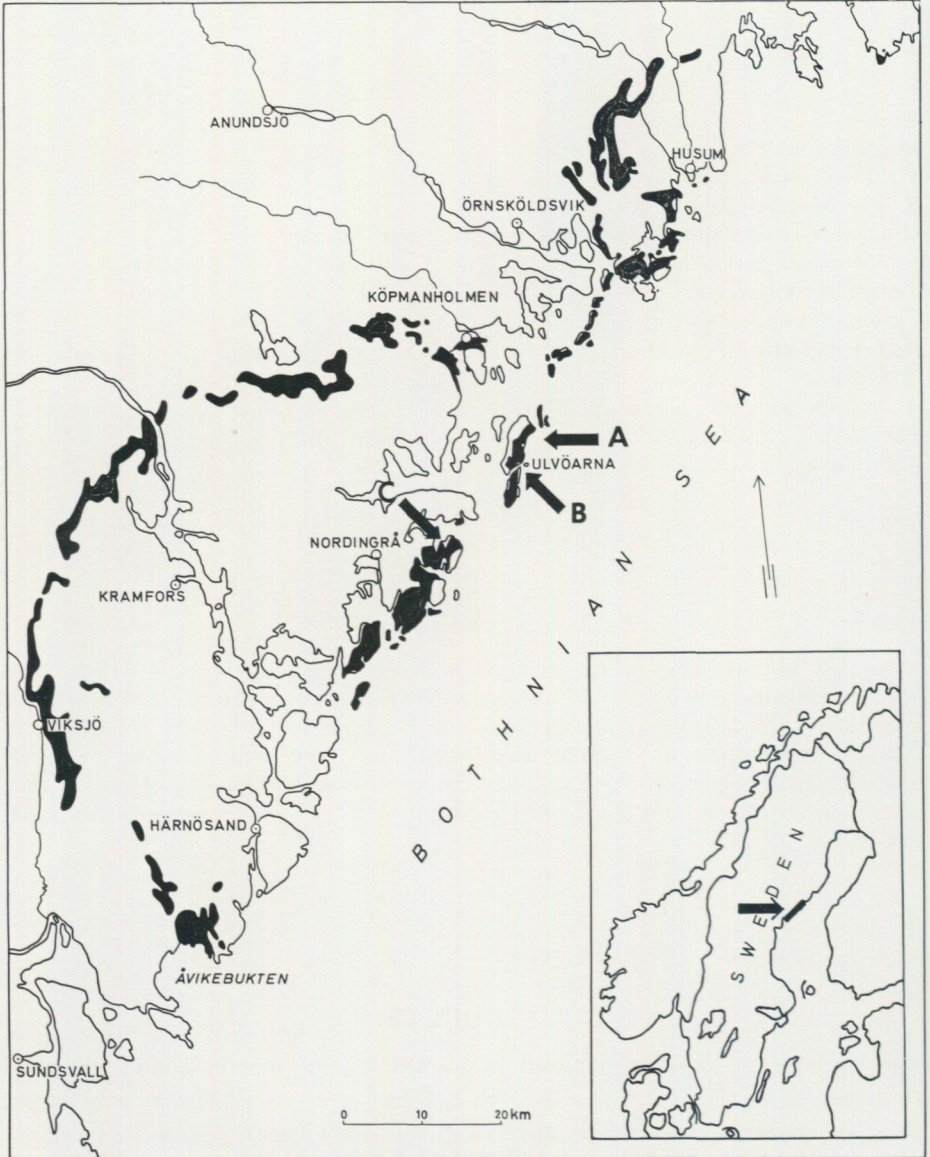


Fig. 1. Dolerite areas (black) in the eastern part of Västernorrland County. Preliminary petrographical map of Västernorrland (partly after Lundqvist 1974). Arrows show the positions of the investigated areas. Norrsand (A), Ulvösundet (B) and Rävsviken (C).



Fig. 2. Distinct rhythmic layering in the Ulvö dolerite, Trysunda island. (Photo S. Å. Larson.)

form sills in Jotnian sandstones and shales. In the area in question they dip gently ($5-25^\circ$) eastwards, towards the Bothnian Sea. An interesting phenomenon is igneous layering, which is very common (at present under investigation by S. Å. Larson). The layering, partly rhythmic, was formed by crystals settling in the magma. (Fig. 2.) The layering is usually conformable to the contacts of the dolerite sheet.

Field observations in the investigated areas have shown the dolerite to be about 250 metres thick, a fact strengthened by gravimetric measurements (Larson and Magnusson, in preparation). The mineral composition of the rock is relatively simple, the most important minerals being plagioclase, augitic pyroxene, olivine, biotite and Fe-Ti oxides with potash feldspar, sericite, serpentine, amphibole, apatite, epidote and quartz as occasional accessories. The rock is usually medium-grained but some irregular bodies and thin veins of coarse-grained dolerite (dolerite pegmatite) are frequently found. (However, they constitute a minor part of the dolerite intrusion).

The samples were taken in the Norrsand area on the island of Norra Ulvön and from the area west of Norra Rävsviken, Nordingrå. (Fig. 1.) (The latter locality was sampled solely for determination of the pole position.)

THE Fe-Ti OXIDES

Fe-Ti oxides were studied using reflectance microscopy. It was found that the main opaque phases were magnetite, ulvite and ilmenite. The grains were usually complex and contained all three phases.

The magnetite may be euhedral, subhedral or anhedral. In the more distinct melanocratic layers, the spinel crystals seem to be euhedral or subhedral. It is assumed that these crystals were concentrated in distinct layers, dependent on rhythmic currents carrying crystals from other parts of the dolerite magma — probably the upper part. The anhedral crystals are thought to be interstitial. To measure the volume percent of different opaque phases, an integration table was used. Thus it was found that magnetite is most common in the central part of the dolerite sheet, where the layering is most distinct. Ulvite forms an intergrowth with magnetite in a discrete network, dividing the host magne-

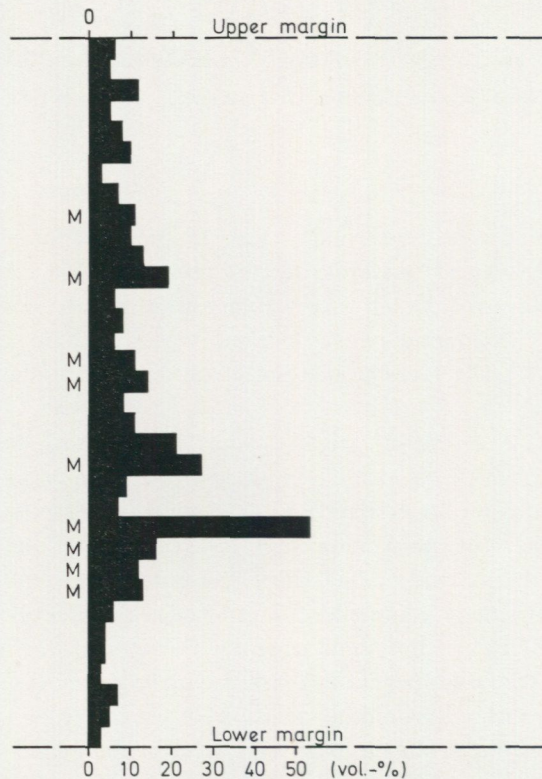


Fig. 3. Modal opaque mineral content of 34 dolerite samples, Norrsand area. The samples are listed in order from the lower towards the upper contact. Melanocratic layer (M).

tite into small areas. The intergrowth can only be observed using oil immersion and magnification of more than 1000 x. The ilmenite concentrates towards the sheet margin. (Fig. 3 shows the modal variation of opaque phases in the Norrsand profile.) Usually it takes the form of lamellar intergrowths along the octahedral planes of the magnetite, but it can also appear as patches and larger areas in magnetite. Ilmenite-magnetite patches are considered to be of secondary origin, and to have formed via ulvite oxidation (Buddington and Lindsley 1964). The patches contain a network of small ilmenite lamellae in a matrix of Fe-Ti spinel. Of course, even primary magnetite may be found together with the patches. Ilmenite may also occur as separate grains.

The olivines usually show cracks containing opaque grains (magnetite), formed by oxidation. As a rule they do not exceed 5 percent by volume of the olivine crystals. The augitic pyroxenes have a violet tint and may contain minute opaque rods (magnetites?), often in a parallel arrangement. The rods are irregularly distributed in the pyroxenes, and their frequency is always less than 5 percent by volume of the host mineral. These rod-containing pyroxenes are themselves irregularly distributed throughout the dolerite sheet.

X-RAY MEASUREMENTS

X-ray measurements were taken using a Philips diffractometer with a scanning speed of $1/4 \theta/\text{min}$ and Cu-radiation. Voltage and current magnitude 40 kV and 20 mA, respectively. It was impossible to obtain distinct peaks from the magnetite-ulvite concentrates. The most distinct peaks of magnetite and ulvite were recorded for $d(220)$, $d(311)$ and $d(440)$. In general peaks were broad and did not separate (cf. Lindh 1973). This phenomenon probably depends on lack of welldefined composition of the two spinel phases, causing different Ti-contents in different parts of a magnetite crystal and in different magnetite crystals, thus causing a continuously varying composition. In the same manner, the Ti-contents in ulvite crystals may vary, but temperature demagnetization of these indicates a narrow compositional variation (see Table 1). Magnetite Ti-content variation is also demonstrated in temperature demagnetization and Curie-point measurements discussed in the following chapters. Mean value of more distinct X-ray peaks shows a composition of approx. 35 mol-% Fe_3O_4 in the ulvite phase and approx. 0 mol-% TiFe_2O_4 in the magnetite phase, i.e., the approximate endpoints of the demixing on the ulvite-magnetite_{SS} series solvus (Nagata 1961).

SUSCEPTIBILITY AND NATURAL REMANENT MAGNETIZATION (NRM)

Susceptibility is proportional to rock magnetite content and is therefore a fast method of evaluating magnetite content (Basley and Buddington 1958). Cross sheet susceptibility (from lower to upper margin), has been measured in situ at Norrsand, Norra Ulvön and Ulvösundet on the northern part of Södra

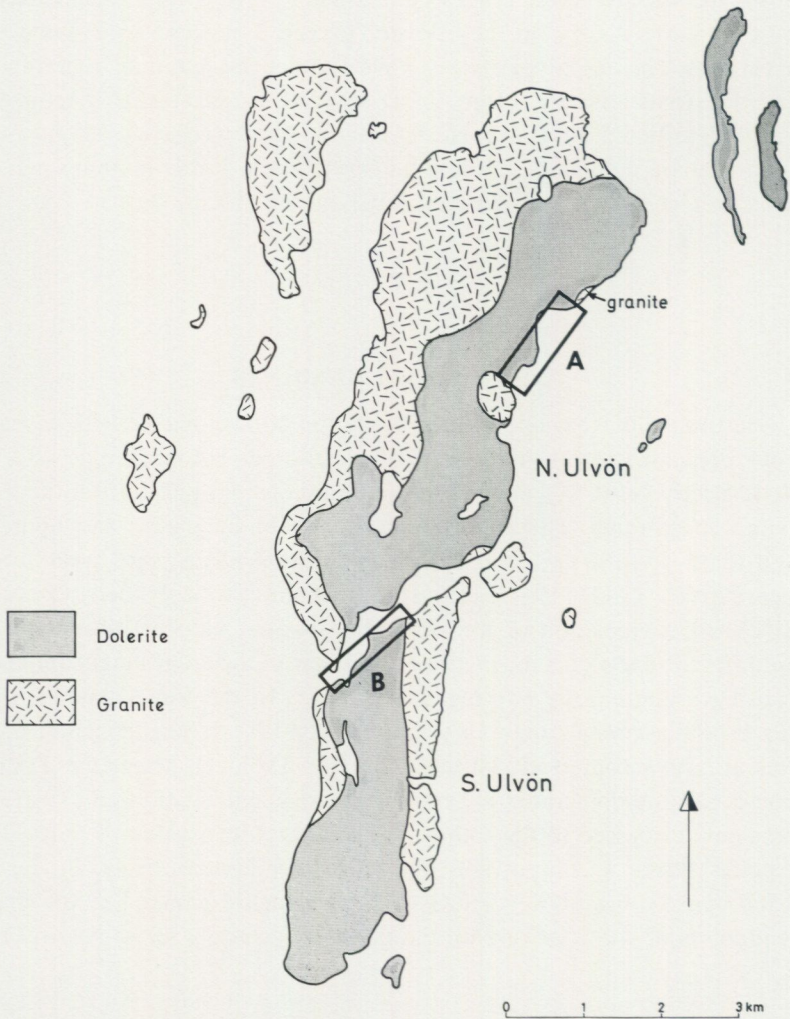


Fig. 4. Petrographical map of the Ulvö region, showing the position of the investigated areas at Norrsand (A) and Ulvösundet (B).

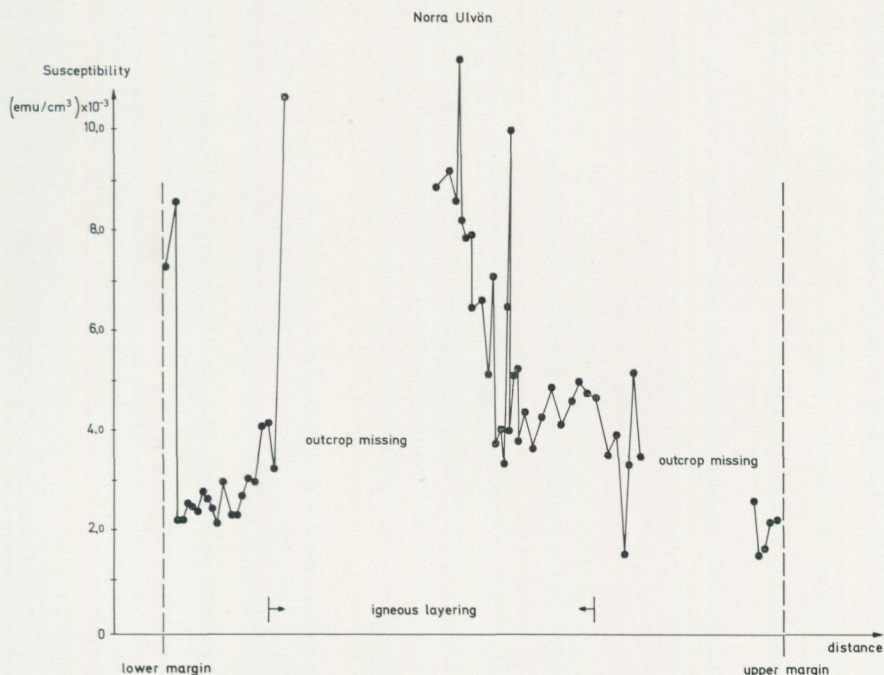


Fig. 5. Susceptibility across the dolerite at Norrsand. Black dots: measured points (in situ).

Ulvön (Fig. 4). The susceptibility meter used was an instrument developed by the Geological Survey of Finland and modified by the Geophysical Department of the Geological Survey of Sweden. It measures a volume of rock equal to a hemisphere of 30 cm diameter.

Susceptibility across upper and lower, relatively homogeneous parts of the sheet is fairly constant and of the same order of magnitude. The layered part possesses a considerably higher and more variable susceptibility. Magnetite crystals in the distinctly layered part of the dolerite are euhedral and concentrated into melanocratic layers. It seems evident that the enrichment of magnetite is caused by rhythmic settling. The lower layered part of the sheet shows highest magnetite content (cf. Figs. 3, 5, 6), decreasing towards the upper margin of the layered part of the sheet (Figs. 5, 6). This indicates a settling process, strongest in its initial phase and then slowly decreasing.

NRM (natural remanent magnetization) intensity measured on cross-sheet orientated surface samples at Norrsand (Fig. 7) shows a similar pattern to that of susceptibility, indicating that minerals carrying remanent magnetization are closely related to those carrying induced magnetization.

It is known that magnetite grains with a diameter of $0.035\text{--}0.057\ \mu$ and $0.057\text{--}20\ \mu$ carrying a magnetization of single and pseudo-single domain type respec-

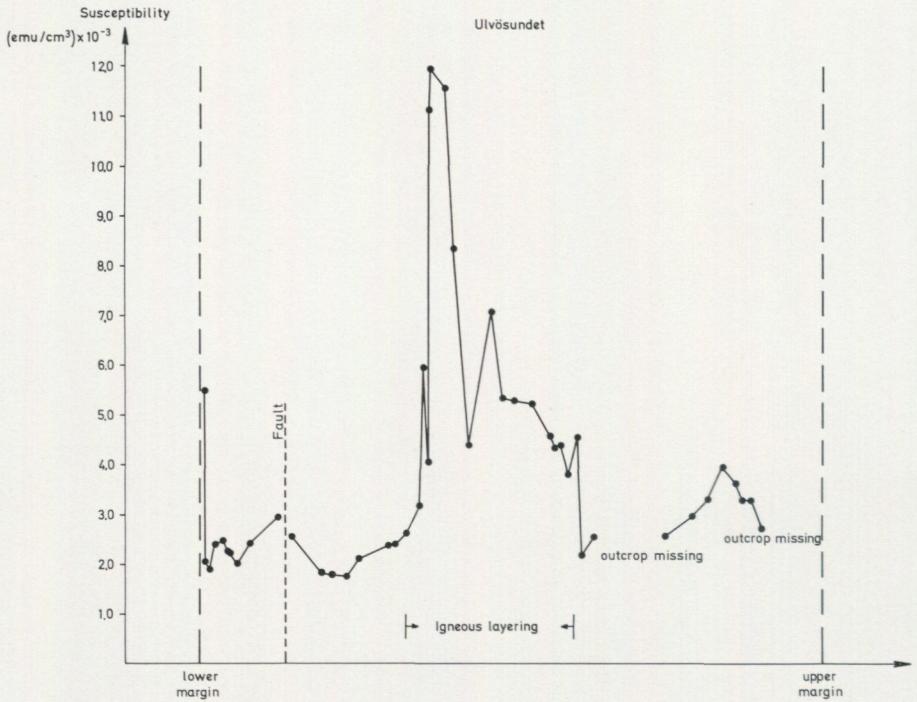


Fig. 6. Susceptibility across the dolerite at Ulvösundet. Black dots: measured points (in situ).

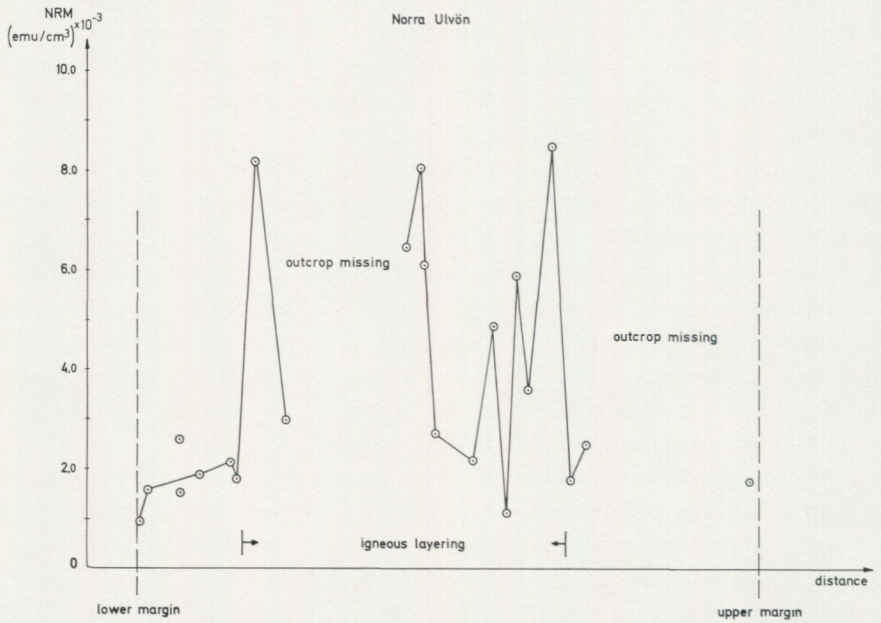


Fig. 7. Intensity of natural remanent magnetization (NRM) across the dolerite sheet at Norrsand. Circles: measured points.

tively contribute little to susceptibility, but largely to thermo-remanent magnetization (TRM). A grain size of 0.22μ gives a ratio of TRM to induced magnetization of 27 (Dunlop 1972). Susceptibility is practically independent of grain size in grains larger than 50μ , but decreases rapidly in smaller grains (Shandly and Bacon 1963). It is convenient to consider grains 50μ or larger to be of true multi-domain type (Stacey and Banerjee 1974). It can be said that the main part of susceptibility is carried by grains of multi-domain type. However, AC-demagnetization, (treated in the next chapter), indicates that remanent magnetization is carried by grains of pseudo-single domain type. It follows that it is the fine network of magnetite and ulvite (intergrowth pattern) which carries the remanent magnetization.

In Ulvö dolerite samples, ilmenite in patches and in a fine network of lamellae splitting the magnetite might also contribute to remanent magnetization. The forming of this ilmenite may be due to oxidation of ulvite intergrown with magnetite. The intergrowth between ulvite and magnetite is probably restricted to areas within host magnetites and it is therefore possible for the magnetite to carry both hard remanent magnetization and magnetization with strong susceptibility. This agrees with the similarity of the cross-sheet NRM and susceptibility curves. (Figs. 5, 7.)

AC-DEMAGNETIZATION

The AC-demagnetization steps chosen are 100, 200, 300, 400, 500 and 800 Oe. Some samples were also demagnetized at 1000 and 1200 Oe peak fields. After demagnetization the samples were measured by Oersted meter or a spinner magnetometer. To fit the spinner magnetometer (high speed spinner magnetometer, JUFJG-JR 3. Institute of Applied Geophysics, Brno), cores were drilled from some of the samples.

Resistance to AC-demagnetization decreases with increasing grain size. Therefore grain size information can be found using AC-demagnetization. Ulvö dolerite samples are hard to demagnetize. This is consistent with Evans' results (Evans et al. 1974), which showed that intergrowth between magnetite and ulvite causes a hard remanent magnetization.

Dunlop (1973) carried out AC-demagnetization on magnetites and correlated the results with grain size. The mean grain size of each sample was determined by electron microscopy. Standard deviation of grain size in each sample, 20—30%. AC-demagnetization curves of Ulvö dolerite samples (Fig. 8) were compared with Dunlop's (1973) standard curves. Except for the region below a RM to NRM ratio of 0.2, Ulvö dolerite curves agree with standard curves. Comparisons of Ulvö dolerite samples to Dunlop's (1973) standard curves

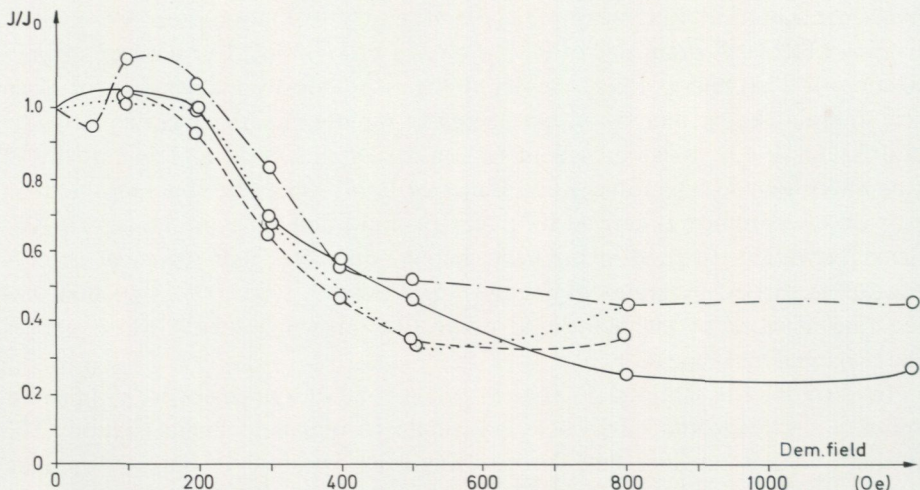


Fig. 8. AC-demagnetization curves of 4 samples from the dolerite at Norrsand. J = Remanent magnetization. J_0 = Natural remanent magnetization (NRM).

show grain sizes of the remanent phase in the region of single domain (SD) — 0.22μ . Three of fifteen samples fall in the SD— 0.037μ region, eight in the $0.037 - 0.076 \mu$ region, one in the $0.076 - 0.10 \mu$ region and the final three in the $0.10 - 0.22 \mu$ region. Two out of three samples from the largest grain size interval come from the dolerite sheet margins (one from the lower and one from the upper margin). Larson et al. (1969) tell us that magnetic grains size 0.5μ (aprox. the limit of visibility in reflectance microscopy) or less are fairly abundant in rocks. Grain size analysis shows that remanent magnetization is of single to pseudo-single domain type.

Patchy intergrowth observed between ilmenite and magnetite is generally coarser than ulvite-magnetite intergrowth (cf. Lundqvist and Samuelsson 1973). Modal analysis show that ilmenite crystals, including patchy ilmenite, are more frequent in dolerite marginal zones. Thus, oxidation of ulvite may cause larger grain size.

Elongated grains are known to carry harder remanence than equidimensional grains. Generally magnetite grains in igneous rocks possess an axial ratio of approx. 1:1.5 (Stacey and Banerjee 1974). The synthetic magnetite grains of Dunlop (1973) probably have nearly the same axial ratio. It is known that the Ti-content of the magnetite_{ss} causes remanent magnetization enhancement. Curiepoint measurements and temperature demagnetization, as treated in a later chapter, show that Ulvö dolerite magnetites are relatively pure (0 — 13 vol.-% Fe_2TiO_4). Grain axial ratio in magnetite and ulvite or ilmenite network intergrowth is unknown. This may cause some error in the estimation of the real grain size of the phase carrying remanent magnetization.

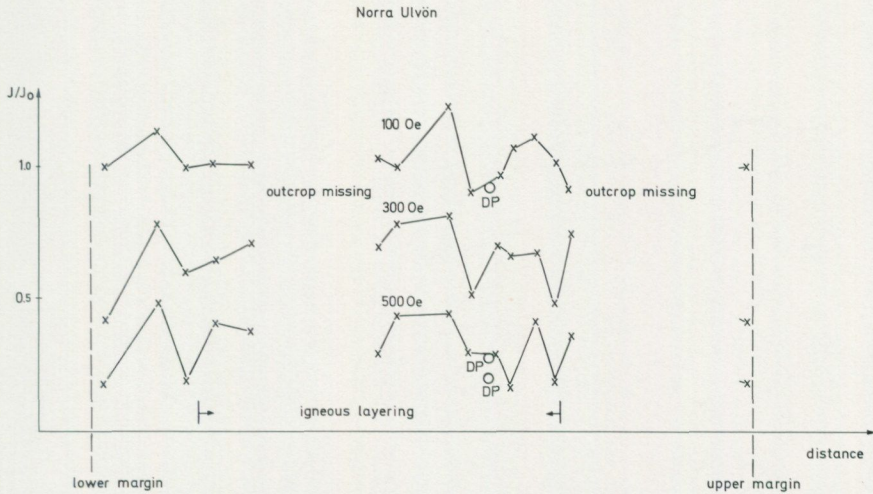


Fig. 9. J/J_0 at different AC-Demagnetization steps (100, 300 and 500 Oe) of samples across the dolerite sheet. Open circles indicate a dolerite-pegmatite (DP). J = Remanent magnetization. J_0 = Natural remanent magnetization (NRM).

Resistance against AC-demagnetization is fairly constant in the dolerite sheet, indicating that fine intergrowth phases are present throughout the sheet (Fig. 9). Note the exceptionally soft remanent magnetization of the dolerite pegmatite (DP), which, in comparison with dolerite in general, possesses a larger magnetite grain size (0.22 — 3.0 μ).

TEMPERATURE DEMAGNETIZATION

Six samples were chosen for temperature demagnetization. All, except number 179 (cf. Fig. 10), belong to the lower, mainly nonlayered, portion of the dolerite sheet (cf. Table 1). Smaller temperature steps were chosen in the region in which Curie-temperature of ulvite and magnetite was expected. (Fig. 10 and 11 show the results of two measured samples.) Two drops in the magnitude of RM to NRM, (J/J_0), are evident. The first indicates the Curie-temperature of ulvite and the second that of magnetite. The first Curie-point (ulvite) at 110 — 140 °C, indicates a composition of 65 — 69 mol-% Fe_2TiO_4 in the magnetite_{ss}. The second slope (magnetite) indicates a relatively pure magnetite composition (97 — 100 %). The proportion of remanent magnetization carried by ulvite and magnetite respectively, can be read from the drops of RM/NRM (J/J_0) of the two phases. It is evident (Figs. 10, 11) that the ulvite carries only a small portion of the remanent magnetization (5 — 15 %) and therefore contributes in

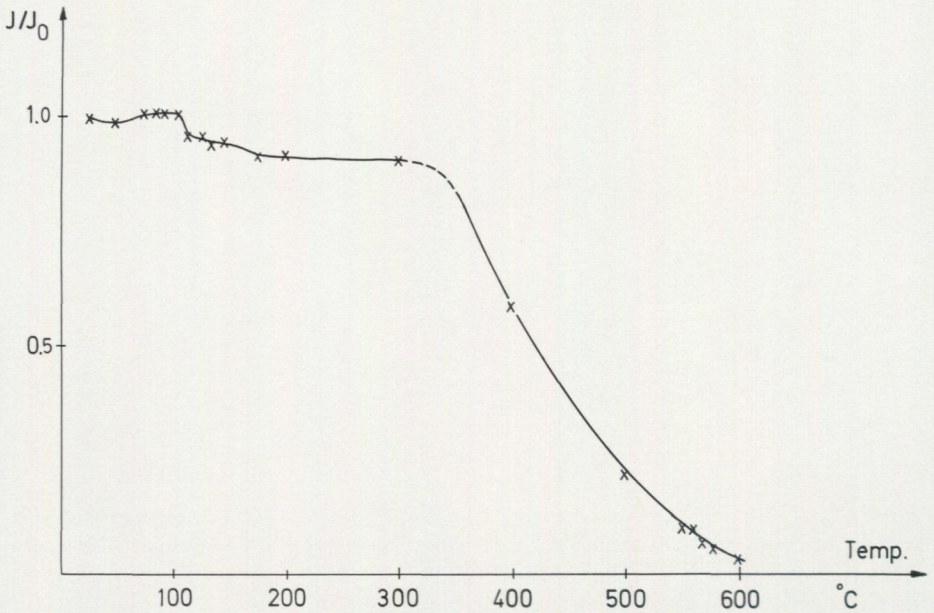


Fig. 10. Temperature demagnetization curve of sample No. 179 from the distinctly layered part of the dolerite (cf. Table 1). J = Remanent magnetization. J_0 = Natural remanent magnetization.

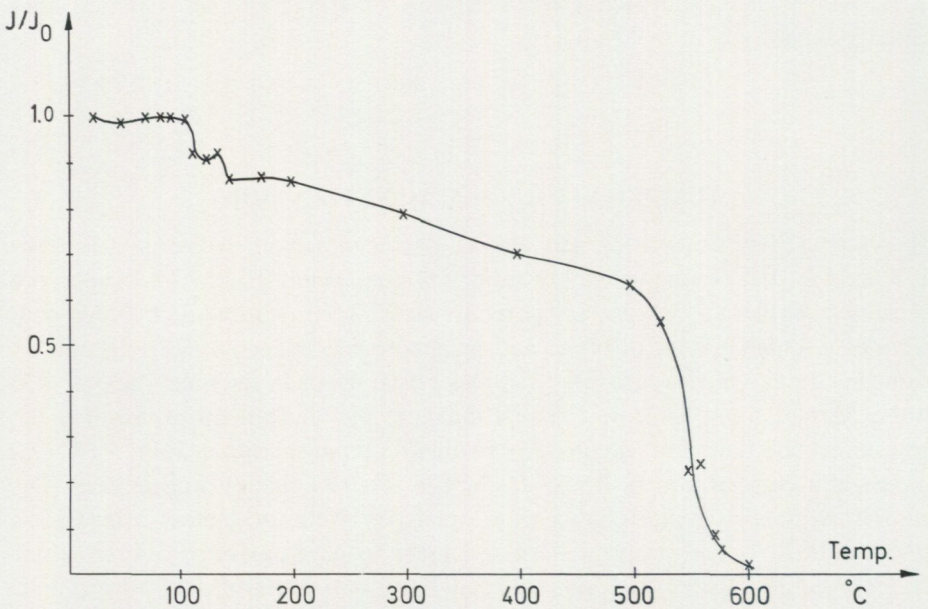


Fig. 11. Temperature demagnetization curve of sample No. 490 from the chilled dolerite margin. J = Remanent magnetization. J_0 = Natural remanent magnetization.

a minor way to NRM. Due to the fact that saturation magnetization of the TiFe_2O_4 - Fe_3O_4 solid solution series (Nagata 1961) is a function of the Ti-content, the ratio of remanent magnetization (RM) of ulvite to that of magnetite as seen from the temperature demagnetization curves (Fig. 10, 11) does not indicate the vol. proportion between the magnetite and ulvite in the phase carrying remanent magnetization. RM of ulvite with Ti-content like the Ulvö dolerite must be multiplied by factor 4 (Nagata 1961) to obtain an estimation of volumetric proportion of ulvite to magnetite. The proportion of ulvite in the remanent phase in the measured samples is 20—30 % (Table 1). Sample number 490 (lower chilled margin of the dolerite) contains a considerably higher ulvite content. The drop in RM/NRM (J/J_0) related to the magnetite phase shows a temperature interval of 50—100°. An interval dependent on grain distribution (Dunlop 1974). A compositional variation effect cannot be discounted. Sample number 179 (Fig. 10) shows a different pattern, which can only be explained by compositional variation. This sample belongs to the distinctly layered portion of the sheet. A rough estimate of the compositional range of sample number 179 would be 0 — 40 mol-% Fe_2TiO_4 (cf. Table 1).

CURIE-POINT MEASUREMENTS

Twentysix samples were measured in order to investigate the Ti-content of the magnetites. The instrument used was a susceptibility-balance-bridge constructed at the Department of Applied Geophysics, University of Århus. It consists of two identical coils surrounded by a glass container chilled with water. The samples were put into a glass tube (inner diameter approx. 4 mm) which was placed in one of the coils, turning the bridge out of balance. The out of balance signal is proportional to the susceptibility of the investigated sample. The bridge was then rebalanced and the required current recorded. The temperature was measured with a thermoelement within the grinded sample in the glass tube. Thermomagnetic curves were recorded (susceptibility versus temperature). Of these seven samples showed a distinct rise in susceptibility, 50—100 °C before Curie-temperature was reached (Fig. 12) an example of Hopkinson's effect.

The susceptibility of single domain (SD) and pseudo-single domain (PSD) magnetite grains are enhanced at low temperatures, but above critical blocking temperature they become super-paramagnetic (i.e. barriers against domain rotation or block-wall motion are overcome by thermal energy), which may result in very large susceptibilities (Bean and Livingstone 1959). Since the blocking temperature for multi-domain (MD) type grains is always close to the Curie-point, susceptibility enhancement is not as significant as in the PSD and SD cases. Magnetization of MD type usually does not show Hopkinson's

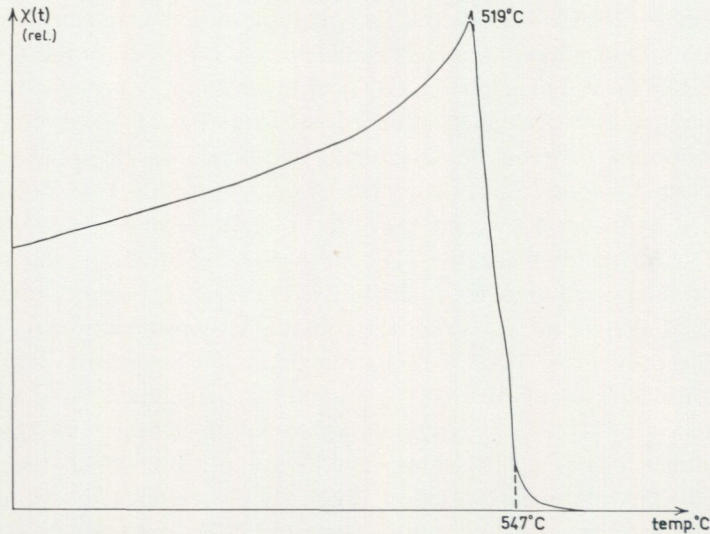


Fig. 12. Thermomagnetic curve. Relative susceptibility versus temperature. Slightly oxidated sample. (Magnetite concentrate.)

effect. The width of Hopkinson's peak is clearly related to the blocking temperature spectrum, a function of grain size (Dunlop 1974). It was expected that susceptibility would drop instantaneously according to spontaneous magnetization loss (Curie-point). During temperature demagnetization remanent magnetization is lost above the critical blocking temperature, resulting in a continuous drop in remanent magnetization across the blocking temperature range. The reason why not all samples show a distinct Hopkinson's effect must be due to a low (SD and PSD) /MD grain ratio and MD contribution masking the PSD and SD grain contribution. AC-demagnetization shows that PSD or SD grains are present in all measured samples. Hopkinson's effect indicates the presence of SD and PSD magnetization in a sample.

A concentration of magnetite from Malmberget, Sweden, was chosen as standard (Fig. 13). A magnetite of low Ti-content (less than 0.1 %). (Cf. Frietsch 1970.) The standard sample dropped distinctly in susceptibility over a small temperature interval of 8 °C. The persistence of short range magnetic order above the Curie-point may explain why the susceptibility does not drop instantly (Stacey and Banerjee 1974). Temperature gradients in measured samples also cause larger temperature intervals (plus other unknown effects). Measured Ulvö dolerite samples show a drop in susceptibility over a much larger temperature interval, which is considered to depend on Ti-content variation. This compositional variation is probably due to oxidation of the ulvite-magnetite_{SS} series. As mentioned before, oxidation may cause a coarsening of the intergrowth network. It is evident from the measurements that the samples

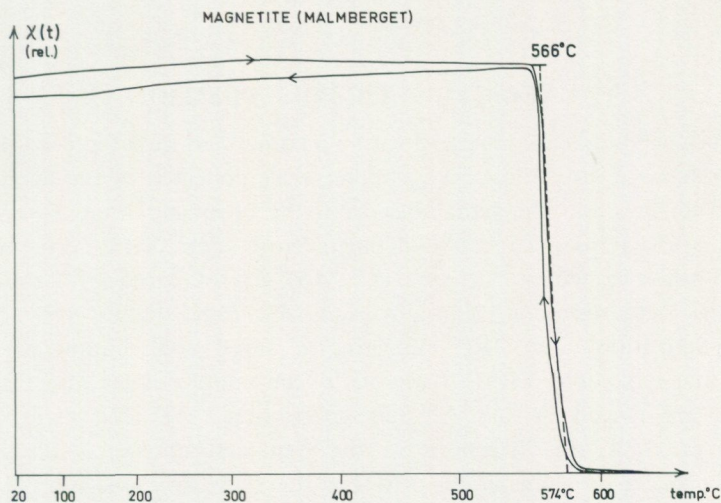


Fig. 13. Thermomagnetic curve. Magnetite concentrate from Oskarsgruvan, Malmberget, Sweden.

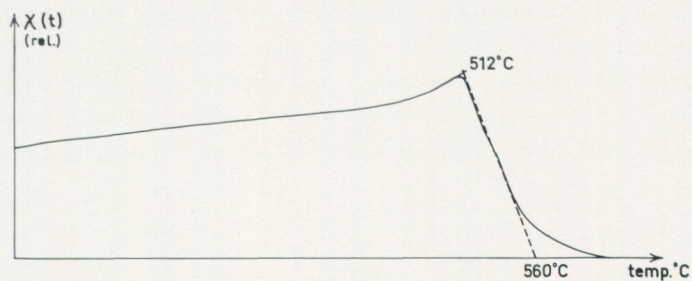


Fig. 14. Thermomagnetic curve. Relative susceptibility versus temperature. Oxidated sample. (Magnetite concentrate).

showing a marked Hopkinson's effect possess a narrow temperature range (i.e. slightly oxidated). These samples belong to the layered parts of the dolerite sheet. (Fig. 14 shows an example of a strongly oxidated sample and Fig. 12 a slightly oxidated sample with marked Hopkinson's peak.)

Two temperatures were measured on each thermomagnetic curve. One temperature was taken from the intersection between the curve tangent before the susceptibility drop and the inflection point tangent. The other was chosen at the intersection between the curve tangent close to zero susceptibility and inflection point tangent (Fig. 14). Obtained temperatures represent the maximum and minimum Ti-content respectively. Inertia shown in the standard sample has been taken into account when calculating Ti-content of other samples. Magnetite Ti-content is listed in Table 2.

PALAEOMAGNETIC POLE POSITION

Twenty fresh samples were loosened with a hammer and then replaced and marked with reference directions. Five samples were collected in the area west of Norra Rävsviken and the remainder from the Norrsand area, Norra Ulvön (Fig. 1). The samples were AC-demagnetized. The NRM directions are fairly well concentrated in one area (Fig. 15), as compared with the present geomagnetic field direction. The directions are only slightly influenced by AC-demagnetization (Fig. 16), indicating a small contribution of viscous remanent magnetization (VRM). Only one of the samples has a direction which is strongly influenced by the AC-demagnetization (Fig. 17). Over 500 Oe demagnetizing field the directions of the remanent magnetization begin to spread. The mean direction of the RM and the standard deviation (α_{95}) were calculated using Fisher statistics. The lowest value of α_{95} was found for 300 Oe demagnetization field (Irving 1964). The results of the AC-demagnetization are tabulated in Table 3.

Intergrowths between magnetite and other Fe-Ti oxide phases, shown to carry the remanent magnetization, are considered to be closely related to the cooling of dolerite magma. As RM directions from the two sampled areas are very similar, no tectonic tilt or rotation of importance has occurred between the areas. Fig. 18 and Table 3 contain data concerning the two sample areas.

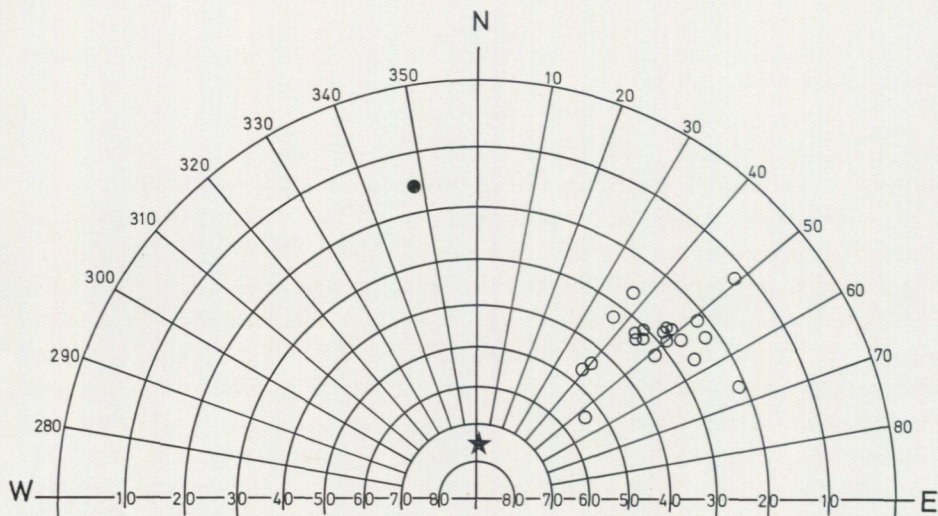


Fig. 15. Direction of NRM plotted in stereographic projection. Open circle: negative inclination. Black dot: positive inclination. Star: present geomagnetic field.

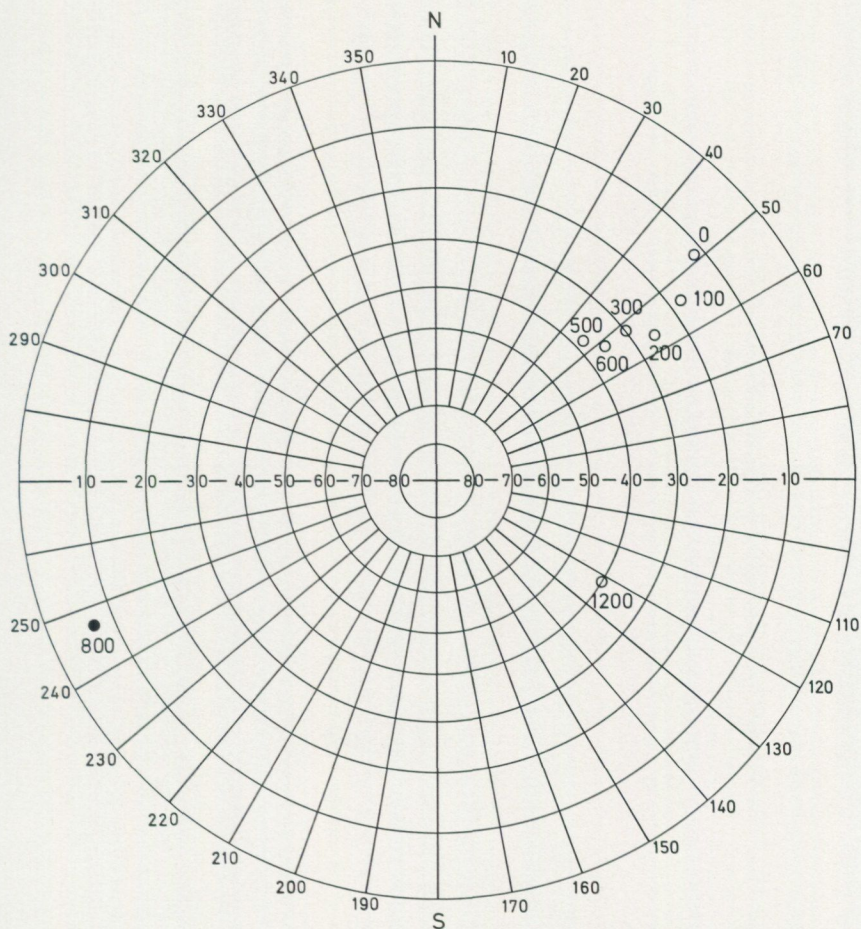


Fig. 16. Direction of remanent magnetization at different demagnetization fields (Oe). (One sample.)

Mulder (1971) has palaeomagnetically researched Jotnian dolerites in the Dalarna area, central Sweden. He considered these dolerites to be influenced by the Caledonian orogeny since their mean pole position was consistent with the Paleozoic pole of "stable Europe". One of Mulder's sample localities (ZDD, Lybergsgnupen) indicates an RM direction which differs from the others. This direction (decl: 31° , incl: -42°) is approx. consistent with the RM direction of the Ulvö dolerite. Dolerites in Finland, of Jotnian Age, have been investigated by Neuvonen (1965, 1966, Neuvonen et al. 1969). Dolerites from surrounding areas thought to be of similar age to that of the Ulvö dolerite are tabulated in Table 4, in which the present investigation is included.

The palaeomagnetic pole position of the Ulvö dolerite is plotted together with

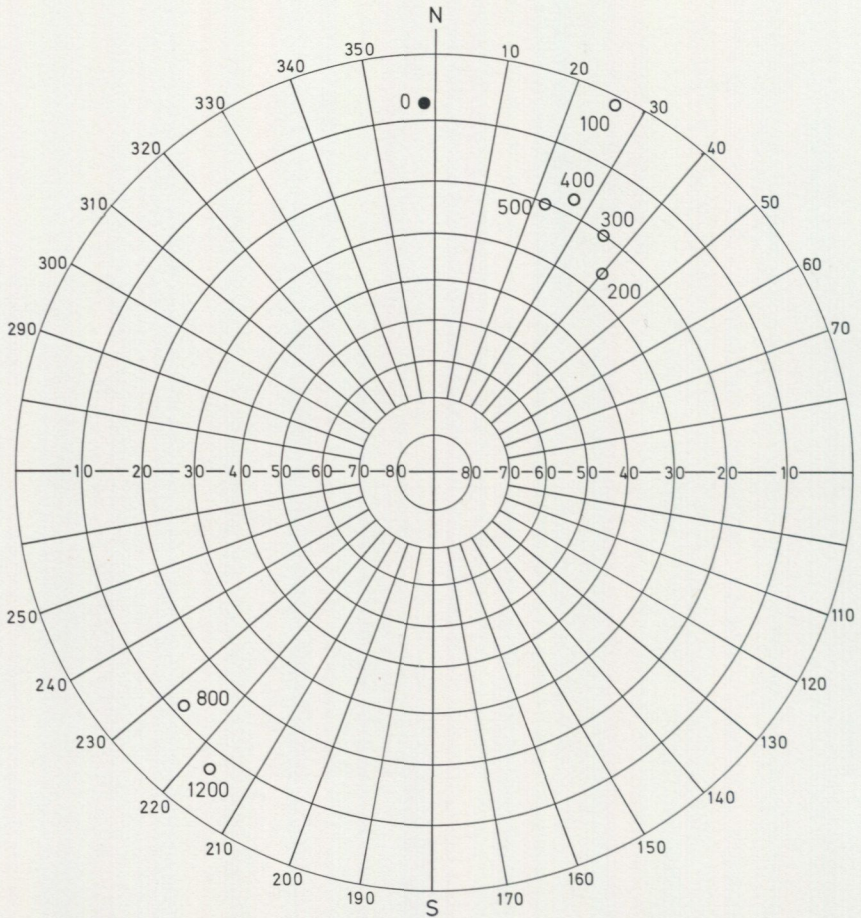


Fig. 17. Direction of remanent magnetization at different demagnetization fields (Oe). (One sample.)

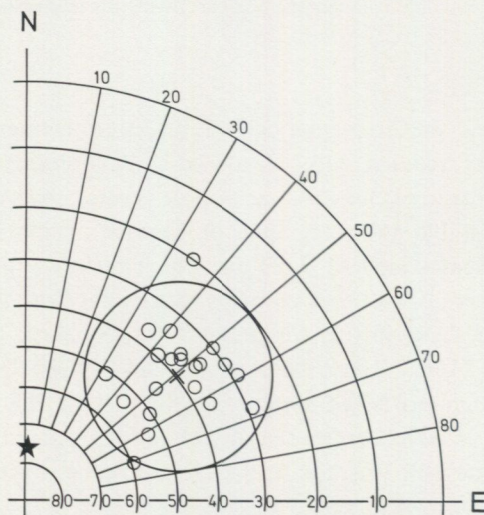


Fig. 18. Remanent directions after 300 Oe AC-demagnetization with the corresponding α_{95} circle of cone of confidence. Cross mean direction of the samples. Small circles: directions of the remanent magnetization for the samples. Star: present geomagnetic field. Stereographic projection.

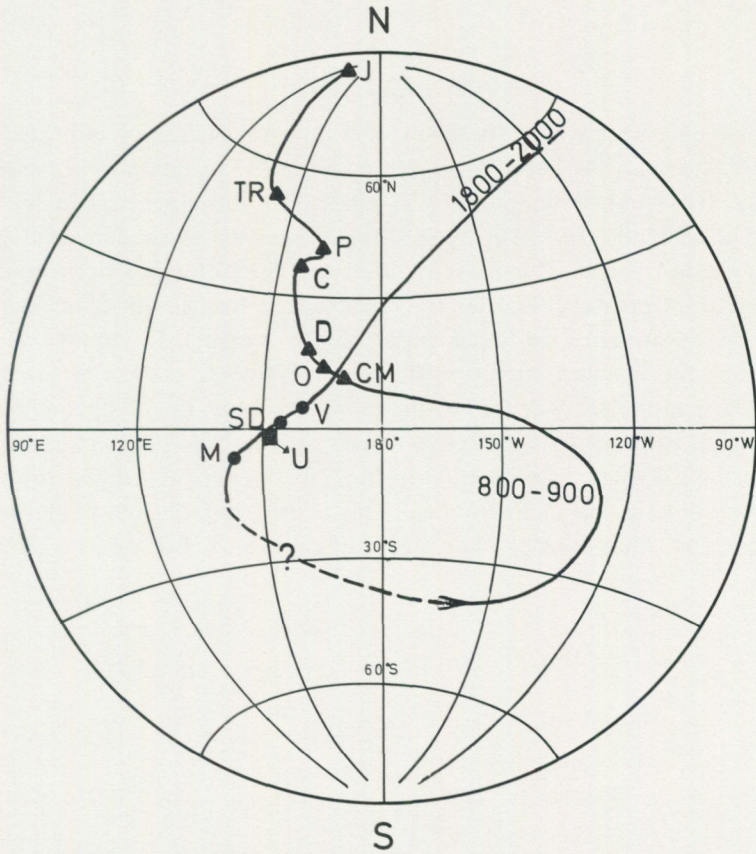


Fig. 19. Palaeomagnetic poles and suggested polar wandering curve for Europe (after Spall 1975 and Creer 1970). Position of the Ulvö dolerite is marked with a square. M: Märket dolerite. V: Vaasa dolerite. SD: Satakunta dolerite (Neuvonen 1965, 1966; Neuvonen et al. 1969). Abbreviations CM-J indicate Cambrian-Jurassic Age.

the wandering polar curve of Europe, Fig. 19, (constructed from data by Creer 1970; Neuvonen 1970; and Spall 1973). The Ulvö dolerite pole position (U) fits in well with the constructed curve and is situated between the poles of Satakunta (SD) and Märket (M) dolerites (Neuvonen 1966 and Neuvonen et al. 1969). This indicates that no block rotation, relative to the Finnish investigated areas, has occurred since the dolerite intrusion.

CONCLUSIONS

The Ulvö dolerite has the character of a layered intrusion, indicated i.e. by rhythmic layering. The latter is visible by the modal variation of feric and salic minerals. It is evident that the Fe-Ti phases are also involved in the settling process of minerals. In some layers opaque minerals show euhedral shape, in others anhedral shape. This may be related to the difference between cumulus and interstitial crystals. The latter crystals have formed in situ, whereas the former began to grow in other parts of the magma. Rhythmic layering is reflected in the variation of susceptibility and NRM. Variation in susceptibility and NRM is also closely related to the modal variation of the opaque phases.

In comparison with the Ulvö dolerite at Ringkallen hill (Lundqvist and Samuelsson 1973) the dolerite at Norrsand, Norra Ulvön, is similar to the upper unit of the dolerite sill at Ringkallen. This is evident from the modal variation of opaque and other mineral phases at Norrsand (S. Å. Larson in prep.) as well

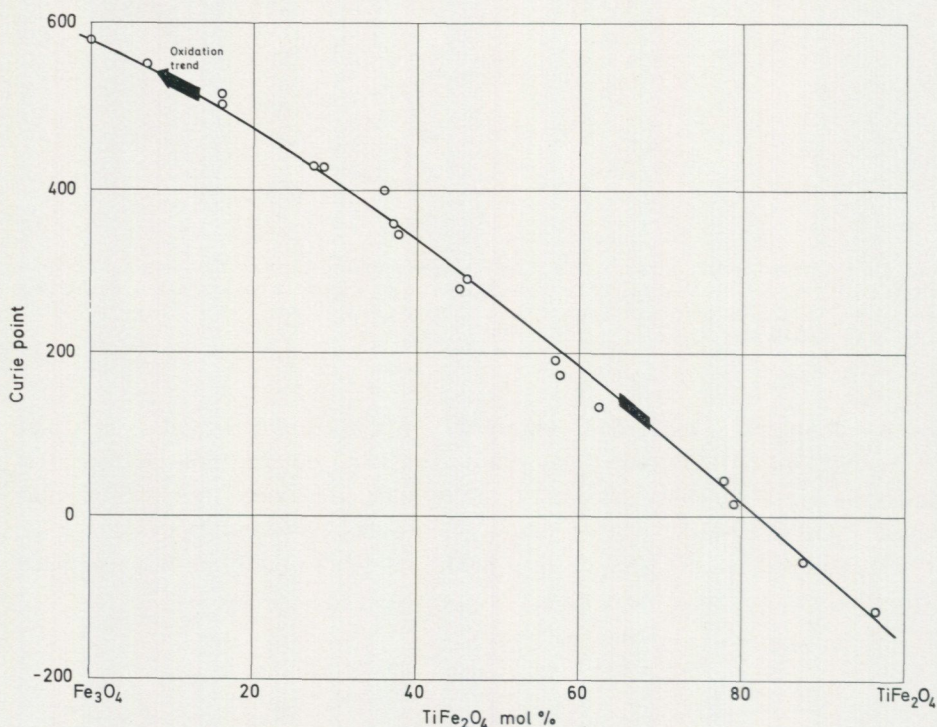


Fig. 20. Curie-temperature versus TiFe_2O_4 -solid solution. Heavy lines on the curve show the position of the composition of Fe_3O_4 and Fe_2TiO_4 resp. from the Ulvö dolerite. (Diagram after Nagata 1961).

as from susceptibility measurements at Ringkallen (K.-Å. Magnusson in prep.) Thus, the multiple intrusive character indicated at Ringkallen (Lundqvist and Samuelsson 1973) can neither be traced at Norrsand nor Ulvösundet.

The Ti-content of unmixed ulvite-magnetite_{SS} series fits well with results expected from the solvus curve (Nagata 1961 p. 84). The Ti-content of the ulvite-magnetite_{SS} series is shown in Fig. 20 (obtained from Curie-point measurements and temperature demagnetization).

Magnetites from layers enriched in Fe-Ti oxides have a mean Ti-content which is higher than those from other layers (Table 2). This is probably due to the difference in the ratio between oxide crystals and interstitial liquid. That is, the oxygen content of the crystal mush in a melanocratic layer is lower than in an "average" dolerite layer. The results from the Skaergaard intrusion, Greenland, show that the magnetite enriched melanocratic layers are less oxidated with respect to Fe-Ti oxides than adjacent leucocratic layers (Vincent and Philips 1954). In the Skaergaard intrusion Vincent (1960) has shown that early cumulus magnetites contain 40—50 vol-% ulvite in a very fine exsolution intergrowth. He further showed that a gradual change from ulvite to ilmenite takes place in the ulvite-magnetite_{SS} series, where oxygen content made it possible. Lundqvist and Samuelsson (1973) proposed a similar process of a formerly unmixed ulvite_{SS} to explain the lack of ulvite in some Fe-Ti oxides from certain parts of Ulvö dolerite at Ringkallen.

Curie-point measurements indicate stronger oxidation near the margins of the Ulvö dolerite, also indicated by grain size coarsening due to oxidation of ulvite. This phenomenon can also be seen from the AC-demagnetization and Hopkinson's effect.

The present investigation involves samples which all are resistant to AC-demagnetization (Fig. 9). This means that the intergrowth pattern which carries the hard remanent magnetization is present throughout the sheet. If the patchy intergrowth between magnetite and ilmenite is a result of ulvite oxidation, it is evident that the ulvite phase was initially present throughout the sheet.

The remanent magnetization is considered to be of primary origin. Thus, the calculated pole position is thought to be identical with the position at the time of the intrusion. The pole position fits in well with Finnish dolerites of similar age and indicates that no major relative block rotation has occurred in this area since Jotnian time.

ACKNOWLEDGEMENTS

Thanks are due to Prof. J. Hospers for his sustained encouragement and great support during our investigation. The authors also wish to thank Drs. H. Henkel and Th. Lundqvist, Geological Survey of Sweden, and Dr. G. Lind, Geophysical Division, Department of Geology, University of Göteborg, who read the manuscript, making valuable suggestions and who were very helpful at different stages of this study. Thanks are due to Prof. K. G. Eriksson, Head of the Department of Geology, University of Göteborg for his support in our investigation.

Thanks are also due to Prof. R. Gorbatshev for putting the equipment of the Palaeomagnetic Laboratory at the Mineralogical Institute, University of Lund, at our disposal. Special thanks to Dr. G. Bylund and his collaborators, Mineralogical Institute, University of Lund whose help has been invaluable. Sincere thanks to Prof. S. Saxov for putting the equipment of the Laboratory of Applied Geophysics, Department of Geology, Århus University, Denmark, at our disposal and to Dr. N. Abrahamsen at the same institute for his guidance in the Curie-point measurements.

"Wilhelm and Martina Lundgrens Vetenskapsfond", the foundation of "Främjande av ograduerade forskares verksamhet" and "Hierta-Retzius stipendiefond" in parts financed the investigation.

TABLES 1—4

TABLE 1. Results of temperature demagnetization measurements.

Sample nr:	172	179	280	295	296	490
Usp _{Tc}	110	110	107	120	107	108-140
Mt _{Tc}	~580	350-580	~580	~570	~560	~580
Usp _{rem.}	30	20	30	30	30	60
Fe ₂ TiO ₄ usp.	69	69	69	68	69	65-69
Fe ₂ TiO ₄ mt.	~3	~0-40	~0	~2	~3	~0

Usp_{Tc} = Curie point of ulvite (°C)

Mt_{Tc} = " magnetite (°C)

Usp_{rem.} = Content ulvite in remanent phase (vol.%)

Fe₂TiO₄ usp. = " ulvite_{SS} (mol %)

Fe₂TiO₄ mt. = " magnetite_{SS} (mol %)

TABLE 2. Ti-content of the magnetites obtained from Curie-point measurements.

THE MAXIMUM T _i -CONTENT OF THE MAGNETITE			
CURIE TEMPERATURE °C		SCHEMATIC STRATIGRAPHY	MOL-% TiFe ₂ O ₄ ss
ANHEDRAL CRYSTALS	EUHEDRAL- SUBHEDRAL CRYSTALS		
519		UPPER MARGIN	11
509			13
528	517	UNLAYERED	
520	501	IGNEOUS LAYERING	ARITHMETIC MEAN OF ANHEDRAL CRYSTALS: 10 ± 0,5
525	525		
523	520		
528	519		
523	518		
525	519		
523	504		
523	510		ARITHMETIC MEAN OF EU-SUBHEDRAL CRYSTALS: 12 ± 2
523	515		
	517		
510		UNLAYERED LOWER MARGIN	13
510			13
518			11
530			9
523			10
THE MINIMUM T _i -CONTENT OF THE MAGNETITE			
575			0
540			7
526			0
557	567		ARITHMETIC MEAN OF ANHEDRAL CRYSTALS: 1
578	558		
576	577		
562	553		
568	550		
572	555	ARITHMETIC MEAN OF EU-SUBHEDRAL CRYSTALS: 2	
584	573		
556	570		
564	565		
580	545		4
574	586		2
574			0
			0
			0
			0

TABLE 3. Direction of remanent magnetization after AC-demagnetization using Fisher's statistics. α_{95} = interval of confidence. k = precision parameter.

Numbers of samples	Peak demagnetization field (Oe)	Declination	Inclination	α_{95} (°)	k
		(°)	(°)		
		mean direction			
20	NRM	45.2	-28.2	13.1	7.1
5	50	48.4	-31.2		
18	100	46.9	-32.3	5.9	34.9
20	200	46.4	-35.5	9.9	12.4
20	300	50.4	-38.7	5.2	39.7
2	350	33.3	-38.2		
16	400	50.8	-38.2	9.2	17.1
2	450	36.2	-39.9		
18	500	39.9	-42.4	19.4	4.1
20	800	39.7	-54.8	67.1	1.2
15	1200	279.4	-67.4	81.6	1.2

TABLE 4. Pole position of rocks in Norway, Finland and Sweden of similar age as the Ulvö dolerite.

Rock unit and country	Pole position		Age	Reference
	Long.	Lat.		
Egersunds dikes, Norway	129 W	22 S	850-950 m.y.	Poorter, 1972
Jotnian basalts, Sweden	174 W	32 N	745-931 m.y., K/Ar	Priem et.al., 1968 and Mulder, 1971
Late Jotnian dolerites				
Sweden	178 E	23 N	late Jotnian	—
Hyperite dolerites,				
Sweden	134 W	12 S	781-1573 m.y., K/Ar	—
Dolerites and basalts,				
Sweden	115 E	10 S	1200 m.y., K/Ar	Dyrelius, 1970
Ulvö dolerite, Sweden	153 E	4 S	1245 m.y., K/Ar	present investigation and Welin & Lundqvist, 1975
Satakunta dolerites,				
Finland	158 E	2 N	970-1330 m.y., K/Ar	Neuvonen, 1965
Vaasa dolerites, Finland	164 E	7 N	Jotnian	Neuvonen, 1966
Märket dolerite, Finland	146 E	6 S	younger than Rapakivi	Neuvonen et.al., 1969

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PRISKLASS C

Distribueras genom

LiberKartor

162 89 VÄLLINGBY

Växjö 1976 C Davidsons Boktryckeri AB

Printed in Sweden

ISBN 91-7158-106-5