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Current research on ilmenite
in the Egersund Province

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REPORT

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Current research on ilmenite in the Egersund Province

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Summary:

Current research on ilmenite in the Egersund anorthositic Province is summarised in the present report. The first step in the prospecting for new ilmenite deposits is considered to be finished. This step contains primarily collection of raw data, such as airborne geophysical measurements, petrophysical studies, recognisance mapping, XRF-field-measurements, thin section studies and microprobe analyses. In addition, more specialised studies like gravimetry and detailed geochemical studies have been applied on the Tellnes deposit. The most promising Fe-Ti - occurrences are so far found to be those at Bakka and Mydland. Both areas contain ilmenite with favourable low amounts of Cr_2O_3 and MgO and very little or no hematite exsolution lamellae. Several of the airborne geophysical maps produced show interesting anomalies that can be used either in the prospecting and mapping of magnetite/ilmenite mineralisations or in the mapping of large scale geological structures. The magnetic maps show many interesting positive anomalies associated with Fe-Ti mineralised layered norites. Petrophysical studies have shown that the Egersund anorthositic Province has unusually high values of remanent magnetism that cause negative magnetic anomalies in parts of the area.

The next step in the investigation is suggested to concentrate on (1) detailed geological mapping and sampling of the areas that at the present time seem to be the most promising regarding Cr and Mg contents in ilmenite, (2) a better understanding of the relationship between data obtained from whole rock chemistry, mineral chemistry and petrography, (3) continue the petrophysical work and start interpretations of the geophysical maps in order to identify new ilmenite deposits, (4) follow-up work on the ground.

Keywords:

ore geology	ilmenite	scientific report
geophysics	mineral chemistry	
petrophysics	XRF	

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INTRODUCTION

The background for the co-operation between NGU and Titania A/S was an inquiry of Titania A/S in the summer 1994 about investigation and evaluation of ilmenite deposits. At a meeting at Titania in the autumn 1994 a project outline was prepared. A project proposal was prepared and accepted for both partners in the winter 1995. It was separated into two main parts, «Egersund area» and «Norway outside the Egersund area». Later on, A/S Olivin became involved in the last mentioned part.

The main goal for the Egersund part of the project, which is the object of the present report, is to find and evaluate ilmenite deposits in the vicinity of Tellnes where the quarry of Titania AS is situated. Such deposits are meant to be additional ores to the Tellnes ore.

In the summer 1995 airborne geophysical investigations were carried out and the first preliminary maps were presented in August. The airborne survey was followed up by ground investigations were the main goals were (1) to sample and evaluate ilmenite mineralised rocks in the norite complex, i.e. mainly those in the Bjerkreim-Sokndal intrusion and those in the Mydland area, and (2) investigate the relationship between the different types of rocks and their magnetic signature with specific view to the influence of remanent magnetism. These investigations have been carried out by Lars Petter Nilsson and Suzanne McEnroe respectively.

In addition Kåre Kullerud has made a geostatistic study of the Tellnes ore, and especially the relationship between the ilmenite composition and the whole rock chemistry. This work is a follow-up of previous work by Kullerud & Bjørlykke (1993) and Rolfsen (1994), and was partly paid by NGU.

It is also started a co-operation with a doctor engineering student at NTNU, Henrik Schiellerup, who will make a thesis on the ilmenite deposits in Egersund and their geological frame. Schiellerup has recognisanced and sampled practically all registered ilmenite deposits in the Egersund area, and has on this background worked out a field report in addition to some new microprobe analyses of Fe-Ti oxides. These data have been entered to the project's PC-database.

The main object with this present report is to summarise and evaluate the present work in the Egersund area, and on this basis propose what is to be done in the future. The project has a frame of 3 years. The first year has focused on sampling raw data. This work can now be considered as finished. The next phase of the project will focus on (1) mapping of the already known deposits and, if possible, detecting new ones, (2) understanding the mineralogy and composition of the different types of deposits. The last phase (1997) will be focused on classifying the different deposits and presentation and evaluation of the results.

Mining, processing and quality requirements of ilmenite

Ilmenite resources are currently being mined from two types of deposits:

1. Sedimentary ilmenite deposits
2. Hard rock ilmenite deposits

Sedimentary deposits are the most common source of ilmenite today. Mineral sands rich in ilmenite are being mined amongst others in Australia (about 40 % of the world's ilmenite production), South Africa, India and Sri Lanka. The major hard rock ilmenite deposits mined today are those at Tellnes in Norway, and Allard Lake in Sorel, Quebeq, Canada.

The quality of the ilmenite in the two different kinds of sources is somewhat different. Hard rock ilmenite deposits contain significant amounts of contaminants such as CaO, MgO, silica, and alumina. The sand deposits, on the other hand, have undergone chemical changes due to their disposal to weathering and leaching processes and in that way change the chemistry. The weathering process leads to an oxidation of FeO to Fe_2O_3, while the leaching process reduces the content of FeO and thereby increase the content of TiO_2. Alteration also leads to variable amounts of contamination by other elements.

The most common use of ilmenite is as a source for TiO_2 pigment. TiO_2 is a white powder with high opacity, brilliant whiteness, excellent covering power and resistance to colour change. To produce TiO_2 pigment two methods are currently being applied (Table 1):
1. The sulphate process
2. The chlorine process

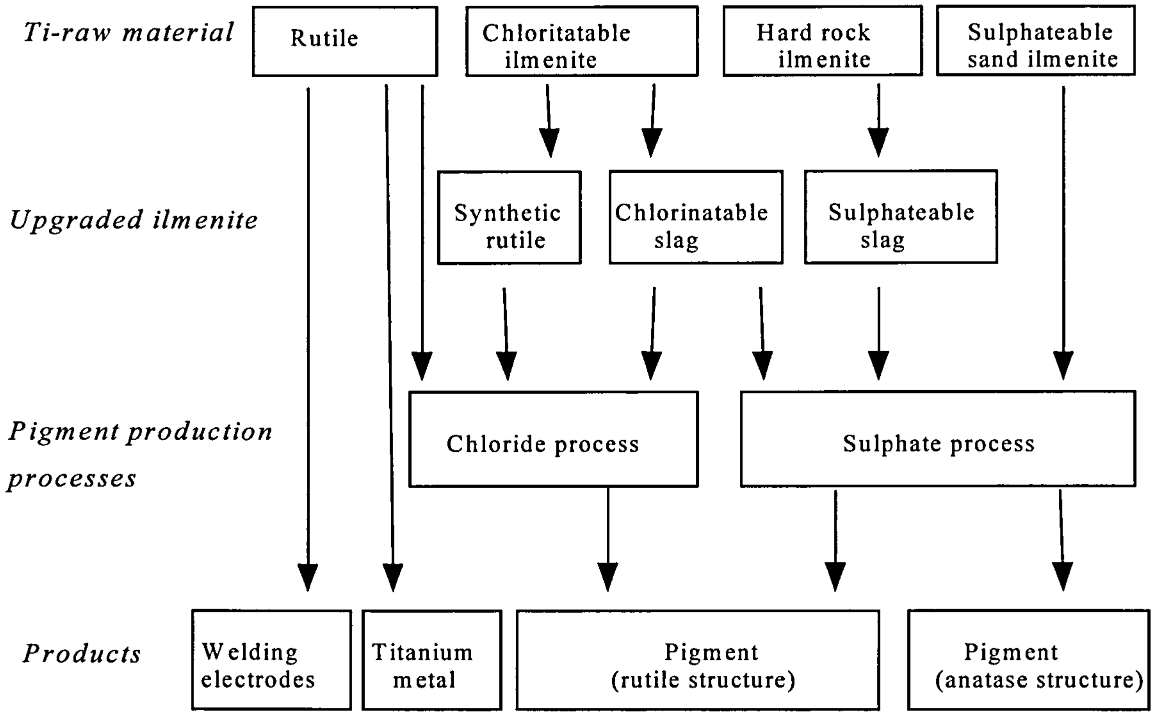


Table 1: Titaniferous minerals from raw material to end products. (From Dormann 1993).

Titania A/S at Tellnes sell their ilmenite product to plants that apply the *sulphate process*. This process is the oldest and is generally less cost-efficient compared to the chlorine process which is the more recent and more technically demanding process, according to Taylor et al. (1996).

The two processes require different qualities from their feedstock (Table 2).

Quality parameters	***Chloride processing***	***Sulphate processing***
Chemical quality, essential:	• low Ca, Mg • low-moderate Mn • low radioactivity (U, Th, and others)	• high reactivity in sulphuric acid (high FeO/Fe_2O_3) • low Cr & V • low-moderate radioactivity (U, Th, and others)
Chemical quality, preferred:	• high TiO_2 • low impurity oxides (Fe, Al, Si)	• low acid insolubles
Physical quality, essential:	• particle size +100 micron	• physical properties not particularly important
Physical quality, preferred:	• high specific gravity • high particle strength	

Table 2: Feedstock quality requirements for TiO_2 pigment products (from Taylor et al. 1996).

In the chloride process feedstocks with minor amounts of impurity oxides such as FeO, Fe_2O_3, Al_2O_3 and SiO_2 are favoured since such components consume chlorine in the process. Low values of alkalies are important because these elements tend to form high boiling point chlorides which eventually may lead to loss of production capasity. In the sulphate process low contents of Cr and V is preferred because these elements are soluble in the sulphuric acid and therefore pass through the process with the TiO_2 causing discolouration in the final TiO_2 product.

Low levels of radioactive elements are important in both processes as they are concentrated in the waste material and therefore might cause environmental problems. This is dominantly a problem for the plants that make use of the chloride process, and is no problem for the Tellnes plant. In addition to the criterias mentioned in Table 2, it is important that the content of MgO is low.

Essential in our present investigation is to find ilmenite rich deposits where the ilmenite has low Cr-, MgO- and V- contents.

GEOLOGICAL SETTING

The Proterozoic South Rogaland igneous province is situated along the coast of southwestern Norway, roughly between Ognabukta to the north and Lindesnes to the south (Fig. 1). It comprises a number of intrusive units emplaced in granulite facies mainly granitic and charnockitic gneisses and migmatites. The basement rocks represent remobilised pre-Sveconorwegian (1.5-1.9 Ga) granitic intrusives and sedimentary and volcanic sequences (Versteeve 1975; Wielens et al. 1980; Demaiffe & Michot 1985; Menuge 1988).

The intrusive suite is dominated volumetrically by three large massif-type anorthosites; the Egersund-Ogna, Håland-Helleren and Åna-Sira anorthosites. The anorthosites were the first intrusive units to be emplaced in the region. Ages as old as 1.5 Ga have been obtained on megacryst inclusions from the anorthosites, probably corresponding to the commencement of a complex emplacement history (Weiss 1986). Final crystallisation took place at 930 Ma, post-dating the latest regional Sveconorwegian deformation by 50-70 Ma (Duchesne in press). The anorthosite emplacement can therefore be considered anorogenic. The Åna-Sira and Håland-Helleren anorthosites have many petrological and isotopical aspects in common and may both be part of a single anorthositic massif (Nielsen 1992). All the massif anorthosites appear to be derived by flotation accumulation of plagioclase crystals in a grossly basaltic mantle derived magma (e.g. Duchesne et al. 1985; Demaiffe et al. 1986).

Major leuconoritic intrusions are found on the island of Hidra (the Hidra leuconoritic body) and north of the Åna-Sira anorthosite (the «outlier» of Garsaknatt/Gasaknuten). They appear not to be related directly with the parental magma of the anorthosites but, along with the noritic units, rather with a jotunitic parental magma giving rise to both leuconoritic, noritic, jotunitic and mangeritic rocks.

A number of noritic intrusions are present in the province. The layered Bjerkreim-Sokndal intrusion is of largely noritic composition and post-dates the anorthosite emplacement. It was folded into a syncline mainly due to gravitationally induced subsidence in the magmatic stage (Paludan et al.1994). The Bjerkreim-Sokndal intrusion displays a 7000 m continuous stratigraphic sequence of rocks from anorthosite to mangerite with major reversals in phase and cryptic layering at levels of magma replenishment. Each replenishment episode defines the base of a mega cyclic unit (MCU). Layered rocks belonging to the Bjerkreim-Sokndal intrusion are found in the Bjerkreim lobe to the north, where five MCU's have been identified (e.g. Nielsen et al. 1996), the Sokndal lobe to the south and the circular Mydland lobe to the east (Fig 2). In both of the latter only the uppermost MCU seems to be represented (Nielsen 1992). Other noritic dikes and layered intrusions include Hogstad, east of Åna-Sira, the Bøstølen layered series, the Storgangen intrusion, the Tellnes ilmeno-norite and the Blåfjell-Laksedal pegmatitic dike, all within the Åna-Sira anorthosite. The Løyning lens is a small layered noritic body, located in the foliated margin of the Egersund-Ogna anorthosite south of Egersund.

Subsequent to the emplacement of the noritic intrusives the jotunitic Eia-Rekefjord intrusion and its related dikes intruded. The main Eia-Rekefjord intrusion is found more or less enveloping the Sokndal lobe to the south and in the associated apophysis, which is in contact with the Åna-Sira anorthosite to the north and east. The Eia-Rekefjord intrusion is also responsible for a dyke system (e.g. the Lomland dyke) intruding the Bjerkreim lobe and the Håland-Helleren anorthosite. A number of jotunitic and mangeritic dikes also transect the Åna-Sira anorthosite. The Tellnes ilmeno-norite lens is a cumulate derived by a complex fractionation event in the jotunitic Tellnes dyke (Wilmart et al. 1989; Duchesne in press).

The acid intrusives; Farsund charnockite, Lyngdal granodiorite and Kleivan granite are found in the southeasternmost extension of the igneous province. They are probably not directly related to the basaltic and jotunitic series but form part of a separate related charnockitic series (Duchesne et al. 1985) which to a large extent may be controlled by crustal anatexis. The emplacement of the acid intrusives marks the end of the syn- to post-Sveconorwegian igneous activity in the South Rogaland igneous province.

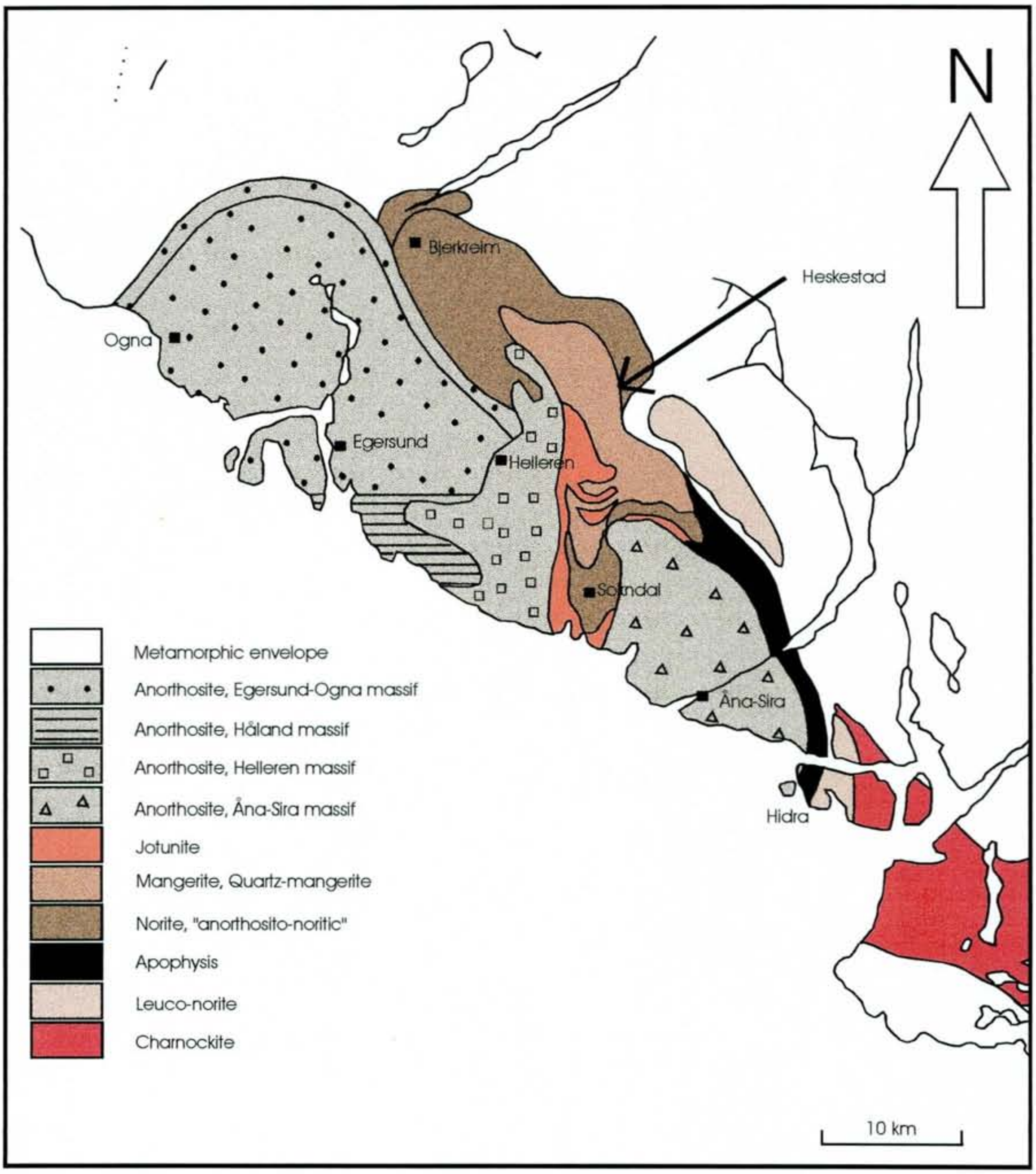


Fig. 1: Simplified geological map of the Rogaland intrusive massifs. (Modified from Duchesne & Michot 1987).

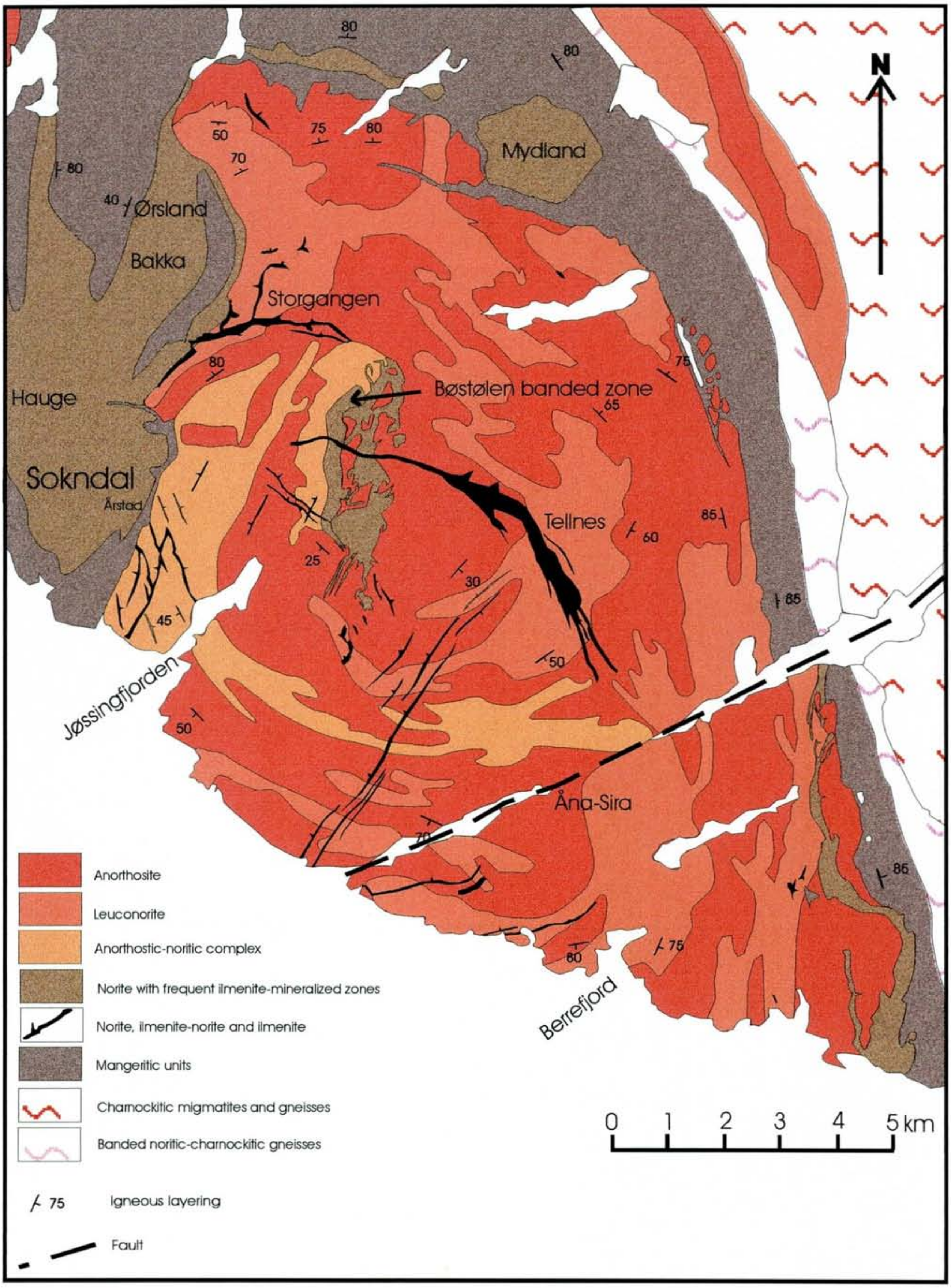


Fig. 2: Simplified geological sketch map of the Åna-Sira anorthosite and related rocks. Modified from Krause & Pedall (1980).

PREVIOUS WORK ON THE ROGALAND FE-TI OXIDES

C.F. Kolderup was the first to recognise the various lithologies in the Egersund area at the turn of the 19th century (Kolderup 1896). Together with J.H.L. Vogt he pioneered the geological research in the region in the beginning of the 20th century. A compilation of analyses and petrographical results on various Fe-Ti mineralisations in the Egersund area was given by Vogt (Vogt 1910). Vogt divided the Fe-Ti mineralisations into relatively pure ilmenite occurrences (Blåfjell, Laksedal and Kydlandsvatnet) and ilmeno-norite occurrences represented by the Storgangen intrusion.

In the mid 1930's the Belgian geologist Paul Michot initiated his work on the South Rogaland igneous province. Michot concentrated on the petrology of the anorthosites and the Bjerkreim-Sokndal intrusion in which he established the cyclic nature of the phase layering (e.g. Michot 1960). He also presented a compilation of the ilmenite occurrences in the Egersund region (Michot 1939) and later suggested a metasomatic origin of the Koldal sheet deposits (Michot 1956). Later on the son of Paul Michot, Jean Michot, began his studies in the region and focused mainly on the genesis of the Rogaland anorthosites (e.g. Michot 1961).

At the Titania plant a compilation of maps and data on known ilmenite deposits were prepared during the second world war (Carlson 1945). Carlson also presented ideas on the genesis of some of the mineralisations, but as his predecessors failed to understand the origin of the layered rocks.

The first detailed study of the Fe-Ti oxide occurrences was made by André Hubaux (Hubaux 1960) who investigated the oxide mineralisations in the Koldal gneissic noritic sheet between the Håland and Egersund-Ogna anorthosites. He vaguely concluded that the oxides in the Koldal sheet were remobilised during tectonism but no further genetic models were presented.

During the second half of the 1960's yet another Belgian, J.C. Duchesne, initiated his study of the oxide minerals in the Egersund province. Fe-Ti micro textures from the Bjerkreim-Sokndal intrusion were described in detail (Duchesne 1970) and Duchesne was the first to conclude that the mega cyclic units in the Bjerkreim-Sokndal intrusion were the result of repeated magma influx (Duchesne 1972). His further work on the Bjerkreim-Sokndal intrusion involved a study of the ultramafic Fe-Ti oxide rich layers in the transition zone between the layered noritic series and the mangerites at Bakka-Ørsland (Duchesne et al. 1987). A vast amount of data and literature have been published by Duchesne and students and co-workers concerning almost every aspect of the South Rogaland igneous province. Studies of the Fe-Ti deposits in the Koldal sheet were presented by Roelandts and Duchesne (Roelandts & Duchesne 1979) concluding that these were the result of fractional crystallisation, not of metasomatosis. A geochemical study of the Tellnes deposit resulted in a rather complicated genetic model involving two separate magma batches to account for the geochemical difference between the ilmenite deposit and the Tellnes main (jotunitic) dyke (Wilmart et al. 1989). The study was inconclusive as to origin of the parental melts. A compilation of the current state of knowledge on the Rogaland Fe-Ti oxide mineralisations along with representative data has been made recently (Duchesne in press).

During the 1970's and the first half of the 80's a German group of geologists from TU Clausthal performed a detailed mapping of the Sokndal lobe, Åna-Sira and surrounding lithological units. The 1:5000 maps are presented in various publications, diplomas and PhD's. Several of the Fe-Ti deposits were described petrographically and mineralogically in great detail but little effort was conducted to constrain the genesis of the mineralisations. The Tellnes deposit was described by Gierth & Krause (1973) and further commented on by Knorn & Krause (1977), who suggested that the parental magma was a residue from the crystallisation of the Åna-Sira anorthosite. An investigation of the Blåfjell-

Måkevatn pegmatite was presented by Krause & Zeino-Mahmalat (1970) and of Storgangen by Krause & Pape (1975). The German work has been compiled in two major papers (Krause & Pedall, 1980; Krause et al. 1985).

Much work in the South Rogaland igneous province has been devoted to the understanding of igneous processes in the Bjerkreim-Sokndal intrusion, anorthosite genesis and the interrelation of the various plutons in the province. All this work, though not dealing directly with the Fe-Ti mineralisations, are important in the genetical, petrological and mineralogical understanding of the occurrence of ilmenite deposits in the region. Unrelated but highly relevant material are found in recently completed Ph.D. theses from Århus University: Nielsen (1992) produced a map of the intensity of igneous layering in the Sokndal lobe (high intensity generally corresponds to a high content of mafics and Fe-Ti oxides in the layered rocks), and a TEM investigation of the micro textures in ilmenites from the Bjerkreim-Sokndal intrusion were made by Paludan (1995), in an attempt to qualify the role of the oxides during the structural evolution of the layered complex. The latter study is of relevance to all deformed ilmenite bearing units in the Egersund area.

CURRENT WORK

The current work includes the following reports (translated):

1. Rønning 1995: Helicopterborne geophysical measurements. NGU-report no. 95.120.
2. Mauring & Gellein 1995: Gravimetrical measurements on the Tellnes quarry. NGU-report no. 95.144.
3. Schiellerup, H., 1996: Fe-Ti mines and prospects in the Egersund area of the South Rogaland Igneous Province. Field report 1995. NGU-report no. 96.051.
4. Kullerud, K., 1996: MgO-content in ilmenite from the Tellnes deposit. Follow-up from previous work. Institute for Biology & Geology, University of Tromsø.
5. Nilsson, L.P. & Staw, J., 1996: XRF-field-measurements (TiO_2-Fe-total) and magnetic susceptibility measurements on mineralisations of Fe-Ti-oxides in the southern part of the Bjerkreim-Sokndal intrusion, Sokndal commune, Rogaland. NGU-report no. 96.048.
6. McEnroe, S., in prep.: Rock-magnetic properties, oxide mineralogy, and mineral chemistry in relation to interpretation of the aeromagnetic map and the search for ilmenite reserves. NGU-report no. 96.060.

Extracts from these reports and additional data are given below.

Fe-Ti occurrences in the Egersund Province

A number of Fe-Ti occurrences exist in the South Rogaland Igneous Province mainly hosted by norites in layered igneous complexes, or in more homogenous Ti-rich intrusive dikes of noritic, ilmeno-anorthositic or mangeritic composition. A description of field characteristics and an evaluation of possible potential can is given by Schiellerup (1996).

The most interesting Fe-Ti deposits outside Tellnes are found in:

1. The *Sokndal lobe* of the Bjerkreim-Sokndal intrusion (southernmost norite in Fig. 1). Here a number of interesting occurrences are found: A; between Soknoelven and Årstadtjørna in the south-western part of the lobe, B; Southwest of Hauge centre, C; at Bakka and Ørsland in the northern part of the eastern lobe. The Bakka (and Ørsland) locality is the most prominent of these and consist of a 50 m thick melanoritic to pyroxenitic sequence with total oxide content of 30 % or higher. The whole Bakka section is nicely revealed in a road cut and would presumably be easy to mine.

2. The *Mydland lobe* of the layered Bjerkreim-Sokndal intrusion (Fig. 2). A central 350 m thick, oxide rich, melanoritic and pyroxenitic stratigraphic sequence contains up to around 20 % ilmenite in collected samples. The lateral extent of the Fe-Ti rich zone has not been fully established but is presumably on the order of 1.5 km. Further field work is needed.

3. The *Storgangen intrusion* (Fig. 2). Mined until 1960, this is the most extensive ilmenite source outside Tellnes in the area. The intrusion consists of layered norites in a dyke up to 50-60 m thick and mineable for a lateral distance of around 1.5 km. Depending on the quality of the Storgangen ilmenite, the dyke should not be underestimated as a valid source.

4. The *Bøstølen intrusion* (Fig. 2) has a somewhat reduced ilmenite potential compared to the before mentioned localities. It has however not been studied in detail as a layered intrusion, and the chemical variation within the intrusion has not been established. Further work is needed to determine the possible occurrence and extent of high quality ilmenite.

5. Several small and medium size occurrences have been found in the area, some of which have previously been mined. These are mainly dikes that are partly mineralised like the Blåfjell-Måkevatn pegmatite dyke, or smaller Fe-Ti rich dikes like the Raunslid and Florklev-Ålgård dikes (see Krause et al. 1985). The importance of these occurrences as ilmenite sources are evaluated as minor.

Petrography of prospects

1 The Bakka section

The Bakka profile covers a 450 m thick stratigraphic section whereof the basal 50 m consist of oxide rich melanorites and pyroxenites (the «Bakka section»). The samples are all laminated with prismatic subhedral Ca-poor pyroxenes and somewhat larger and partly recrystallised plagioclase crystals set in a matrix of Fe-Ti oxides. Ilmenite and magnetite in general appears in roughly similar amounts of up to 20 % in the mineralised Bakka section. The grain sizes in general lie in the 1-4 mm range. Ca-rich pyroxene becomes a cumulus phase within the first basal tens of meters and are present at the base of the Bakka section only as an exsolved phase. At the top of the profile the pyroxenes becomes poikilitic. The whole profile additionally contains an appreciable amount of apatite (around 5 %) and accessory biotite and sulphides (pyrite, chalcopyrite and pyrrhotite/pentlandite).

No visible exsolution of hematite from ilmenite can be observed in the Bakka section and only in the highest stratigraphic level represented in the profile is exsolution evident. Magnetite exsolve at least three generations of spinel including pure spinel, hercynite and zinciferous and chromian hercynite. Contacts between ilmenite and magnetite are generally rimmed by exsolved hercynite.

2. The Mydland lobe

Petrographical data from the Mydland lobe is sparse, but the rocks (Fig. 3) can be considered identical to the Bakka profile in terms of mineralogy. However, the modal distribution of phases are somewhat different, the central melanoritic and pyroxenitic section being more oxide rich and dominated by ilmenite (ilmenite/magnetite roughly around 60/40). As in the Bakka section maficity rise at the appearance of cumulus Ca-rich pyroxene and the Bakka section and central Mydland are likely to have crystallised contemporaneously from the Bjerkreim-Sokndal magma chamber. The total ilmenite content may be as high as 25 %.

Below the central mineralised zone hematite exsolution in ilmenite is observable and prominent. No exsolution have been observed in the central zone. Magnetite again contains at least three generations of exsolved spinel phases in addition to ilmenite.

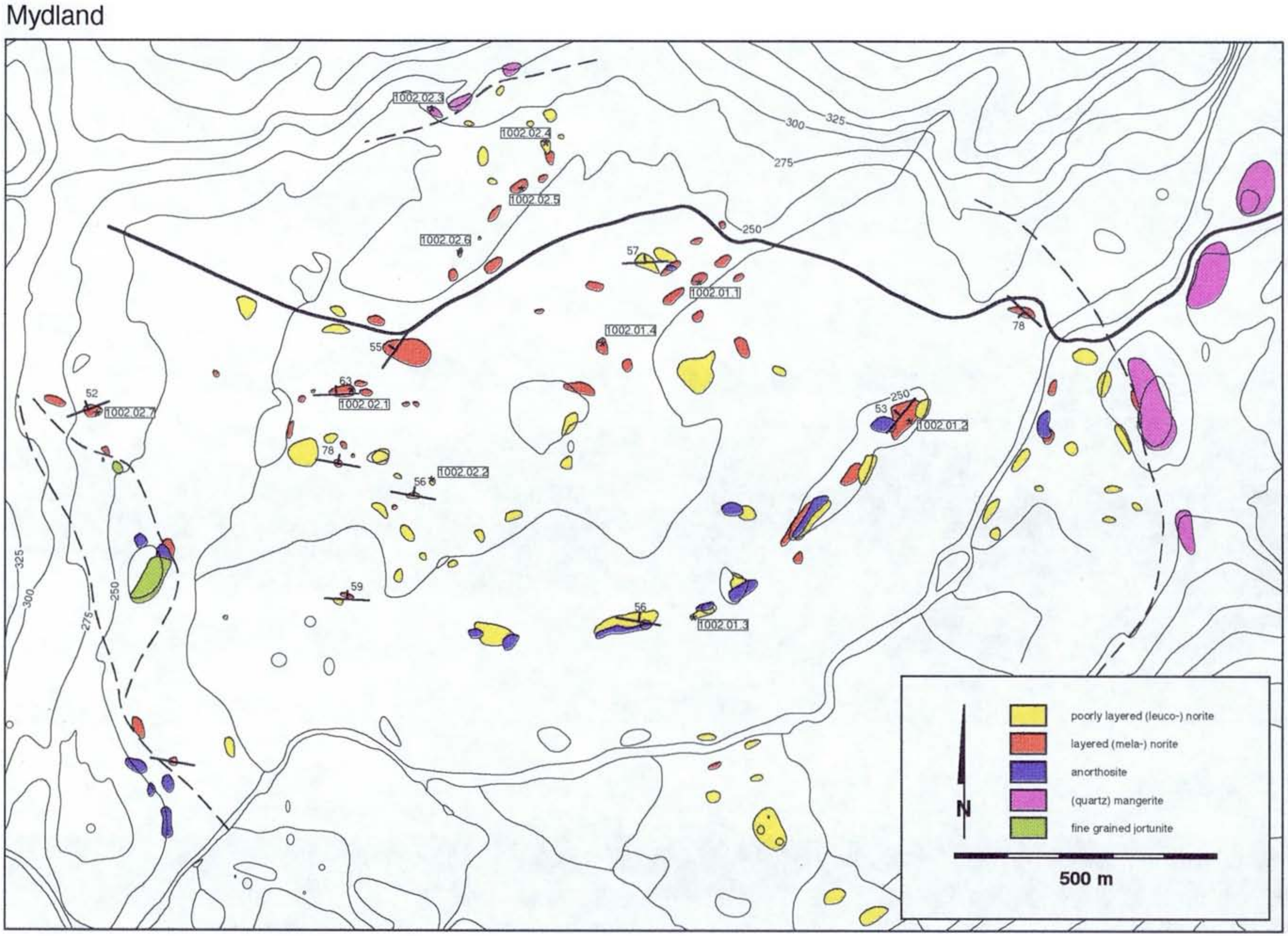


Fig. 3: Outcrop map of the Mydland norite lobe (from Schiellerup 1996), including sample localities referred to in the text and in Appendix.

3. The Storgangen intrusion

The Storgangen norites (Fig. 2) are characterised by relatively equigranular textures with grain size variation affecting all constituent phases. In general the grain size varies from 0.4 to 2 cm with the coarse samples dominantly at footwall and hanging wall contacts. All cumulates are laminated with the oxides partly recrystallised into pressure fringe like textures around prismatic Ca-poor pyroxene. The rocks are dominated by Fe-Ti oxides, subhedral and often deformed Ca-poor pyroxene and equidimensional, undulatory and partly recrystallised plagioclase. The average composition is around 20-50 % ilmenite, 5-20 % magnetite, 20-40 % Ca-poor pyroxene and 10-30 % plagioclase with considerable variability due to modal layering. Below the hanging wall contact Ca-rich pyroxene becomes a cumulus phase implying an up-sequence-up relationship through the phase layered cumulates. Accessory phases are apatite, biotite, green spinel, pyrite, chalcopyrite and pyrrhotite/pentlandite. The total sulphide content is variable but generally less than 2 %.

Exsolution of hematite in ilmenite is clearly visible but not prominent. Two generations of exsolution can be identified. A distinct zoning in the amount of exsolved hematite in hemo-ilmenite adjacent to magnetite implies a post-exsolution reequilibration. Contacts between hemo-ilmenite and magnetite grains are generally characterised by a rim of exsolved hercynitic spinel. Bimodal size distribution among exsolved spinel lamellae in magnetite equally implies that two generations are present. No ulvöspinel/ilmenite has been observed in magnetite.

Mineral chemistry

H. Schiellerup have so far studied the mineral chemistry on 13 polished thin sections from Storgangen (Strosse 84), the Bjerkreim-Sokndal intrusion (Bakka section and olivine bearing basal part at Årstadtjørna) and the central mafic part of the Mydland lobe (Fig. 4 & Appendix 1). In addition, S. McEnroe has made analyses related to petrophysical studies (McEnroe 1996). Below, Schiellerup's study is described, while extractions from McEnroe's study are given in a later section.

Analyses were performed on the NGU/IKU electron micro probe at IKU in Trondheim. The instrument is a JEOL superprobe 733 equipped with three crystal spectrometers and an EDS detector. Acceleration voltage was maintained at 15 kV and the instrument operated with a beam current of 15 nA (sufficiently low to avoid Na evaporation during analyses). Cr and Ni were analysed by WDS, all other element by EDS. Counting times for Cr were set to 40 seconds and 100 seconds for Ni (live time). In general the Cr detection limit lies between 0.01 and 0.02%. Ilmenite grains were analysed both by spot measurement and by scanning a 200x300 µm area for hemo-ilmenite whole grain compositions. Similar procedures for magnetites did not produce any significant differences. The WDS analyses are only accurate by spot analyses.

Zonation in hematite content in hemo-ilmenite is observable in thin sections where ilmenite is in contact with magnetite. Profiles transecting ilmenite-magnetite contacts in Storgangen and Bakka section samples do not reveal any significant chemical zoning. The reason presumably is, that analyses were performed by spot measurement and that ilmenites from both localities display limited hematite exsolution. Grain profile data have therefore not been included in Appendix 1.

Bakka section

All major phases present in four thin sections from the Bakka section (Fig. 2) have been analysed. The cryptic variation in ilmenite (spot and whole grain), plagioclase and Ca-poor pyroxene are presented in Fig. 5. Stratigraphic 0 have been set at the base of the road cut east of Bakkatjørna. The densely layered and Fe-Ti rich sequence is located between the two lowermost samples 1006.03.8 and 1006.03.3 i.e. the basal 50 m of the profile. Both NiO_2 and Cr_2O_3 are barely detectable in ilmenite and the stratigraphically dependant MgO content lies around 2.5 % in the mineralised part of the section. The difference between spot and scan measurements indicates an amount of exsolved hematite in the basal part of the section of 2-3 %. The uncertainties on this estimate is likely to be considerable. Cryptic variation in plagioclase and Ca-poor pyroxene is distinct with a 12 En% variation in the 450 m profile.

As the cryptic variation is conspicuous and systematic through the whole profile, the mineral chemistry in the Fe-Ti rich zone can be considered fairly well constrained. However, further data are needed to resolve smaller scale variations and possible modal dependency of mineral chemistry.

Årstadtjørna olivine bearing cumulates

The Årstadtjørna cumulates are the most primitive rocks found in the Sokndal lobe. Mineral chemistry here is of interest as these rocks have crystallised more or less directly from the uncontaminated parental magma. Equivalent data from the Bjerkreim lobe of the Bjerkreim-Sokndal intrusion yield somewhat more evolved compositions but olivine and Ca-poor pyroxene do not coexist in the basal units of MCUIV. Only one sample has been analysed from the olivine bearing basal cumulates (Fig. 4).

Mydland

Only two samples from the central mafic Fe-Ti rich part of the Mydland lobe have been analysed (Fig 4, locations on Fig. 3). However, these two samples indicate a significant stratigraphic control on the mineral chemistry in the zones of mineable oxide potential. Ilmenites from the two samples have Cr_2O_3 and NiO contents of 0.01 % or lower and exsolution of hematite in the ilmenites is inferred to be of minor importance. Sample 1002.01.2, which is deeper in the stratigraphy, has an MgO content similar to samples from the Bakka section of 2.16 %. The MgO content decreases up-sequence, and in sample 1002.01.1, which has been collected near the centre of the central oxide-rich melanoritic section, it has been measured to 1.40 %. Further decrease may be expected up-sequence and additional field work combined with detailed investigations of the variation in mineral chemistry through the melanorites may prove extractable high quality (low Cr and Mg) ilmenite resources.

Storgangen

Six drill cores from Storgangen (strosse 84) have been analysed illustrating the cryptic variation from footwall to hanging wall in the eastern part of the mined section (Fig. 6). Variation in Cr and Ni content in ilmenite cannot be resolved but the Cr_2O_3 content in general lie between 0.01 and 0.02 % (Fig. 4). This is somewhat higher than the Bakka and Mydland samples. The low Cr_2O_3 content is partly inconsistent with data from oxide separates published by Duchesne (in press). Cryptic variation can be observed in both ilmenite, plagioclase and Ca-poor pyroxene, though the variation is indistinct. Especially the MgO content of ilmenites is variable and decreases from 3.5 % at the base to around 2 % at the hanging wall contact.

The difference between FeO-content measured during spot and scan analyses lies between 2 and 3 % (Fig. 4), indicating that the amount of exsolved hematite in ilmenite is minimum 5 % in the whole profile.

Plagioclase compositions varies between An_{53} at the base (footwall) and An_{48} beneath the hanging wall contact (Appendix 1). Similarly, Ca-poor pyroxene evolves from En_{73} to $En_{68}$from footwall to hanging wall contacts. The cryptic layering therefore corroborates the up-sequence-up interpretation based on a comparison with the neighbouring Bjerkreim-Sokndal intrusion and the phase layering observed in the cumulates (Schiellerup 1996). Analysed plagioclase from Storgangen are more primitive than the plagioclase of both the Bakka section and the primitive cumulates at Årstadtjørna. However, coexisting Ca-poor pyroxenes in the Storgangen intrusion display more evolved compositions than the Årstadtjørna cumulates, and the discrepancy in equilibrium compositions requires chemically disparate magmas or different P-T conditions of crystallisation. Along with the presence of plagioclase megacrysts in the Storgangen intrusion this observation is not in favour of any consanguinity of the Storgangen and Bjerkreim-Sokndal magmas.
Clearly further analytical work is needed.

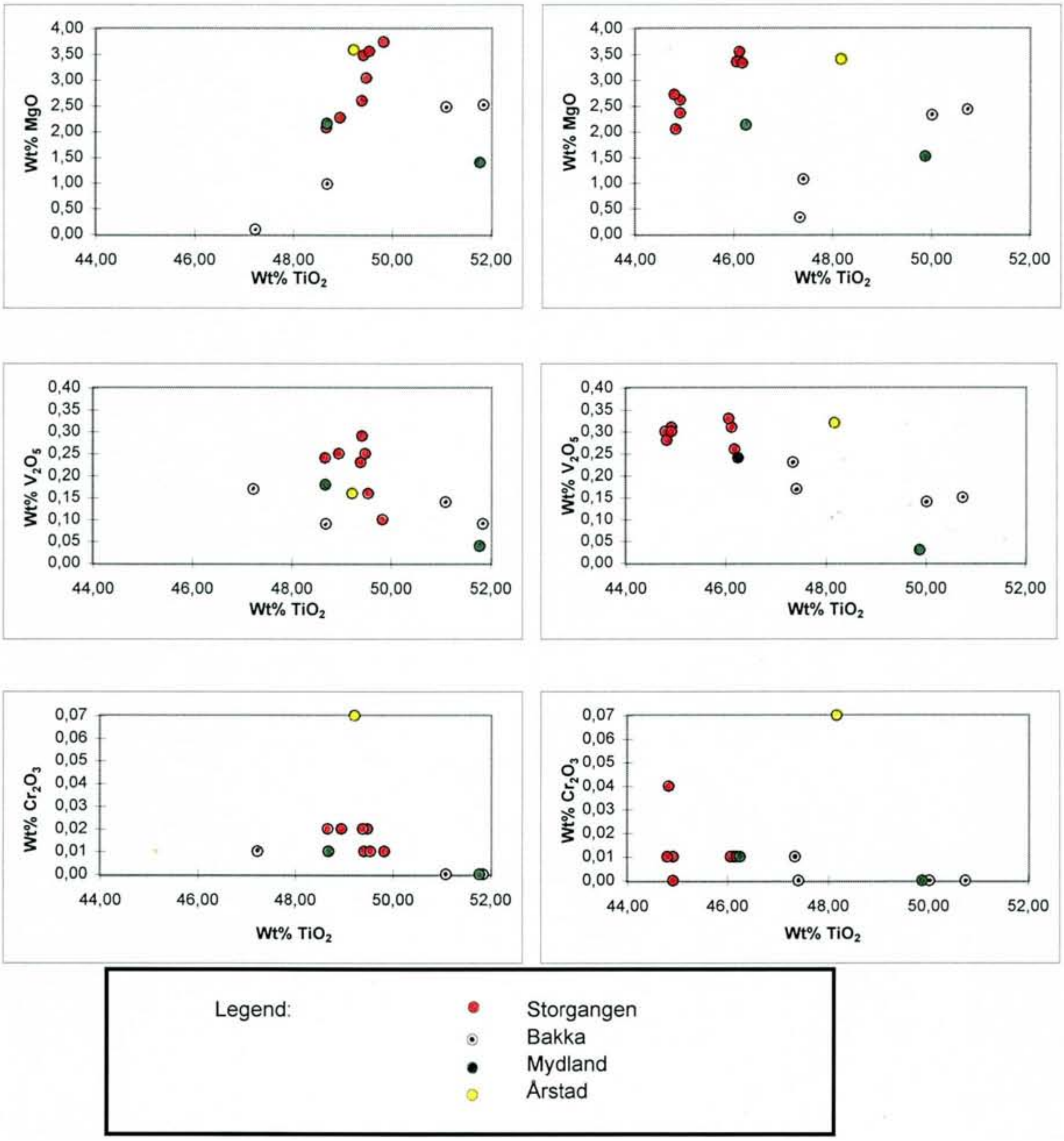
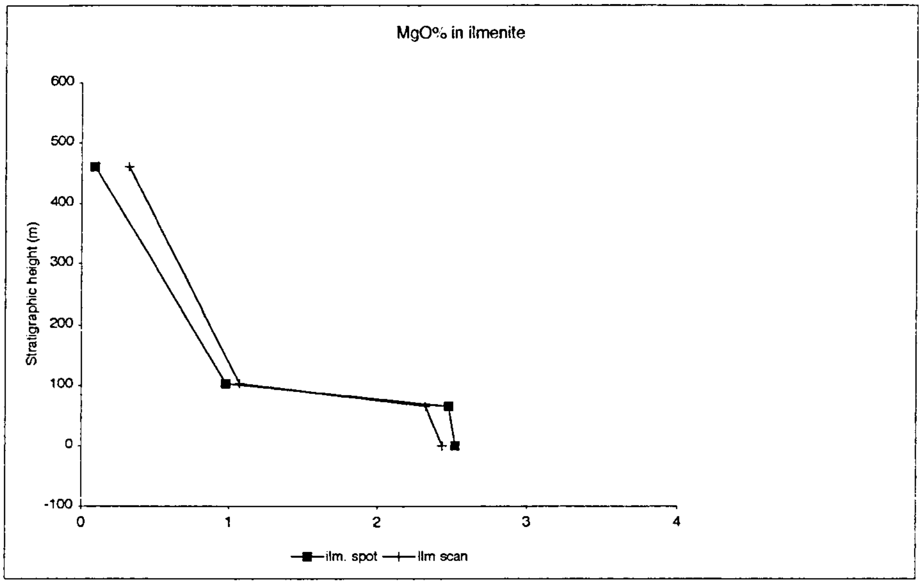
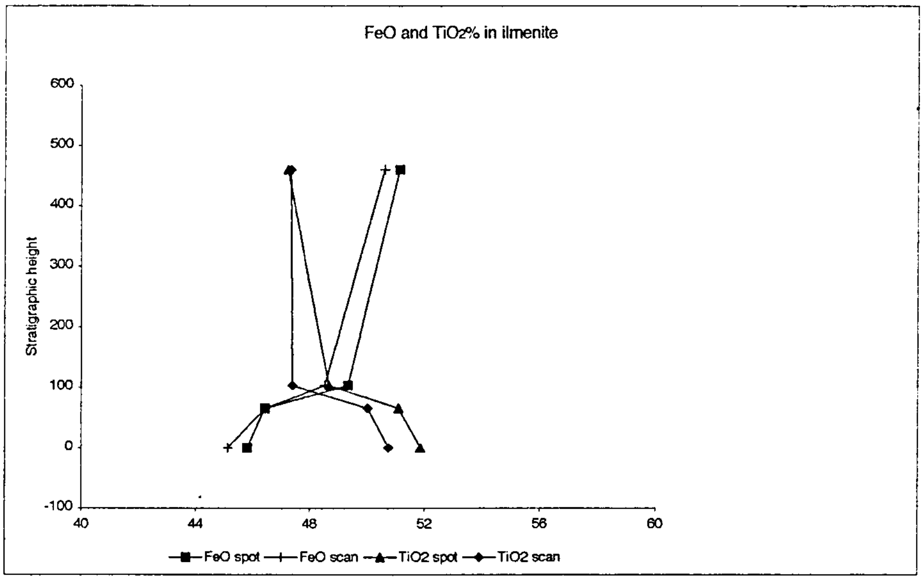


Fig. 4: Plots of MgO, V_2O_5, Cr_2O_3 versus TiO_2 in ilmenite from different localities. In the right hand plots the beam of the microprobe has bean defocused, while a focused beam has been applied on the left hand plots.





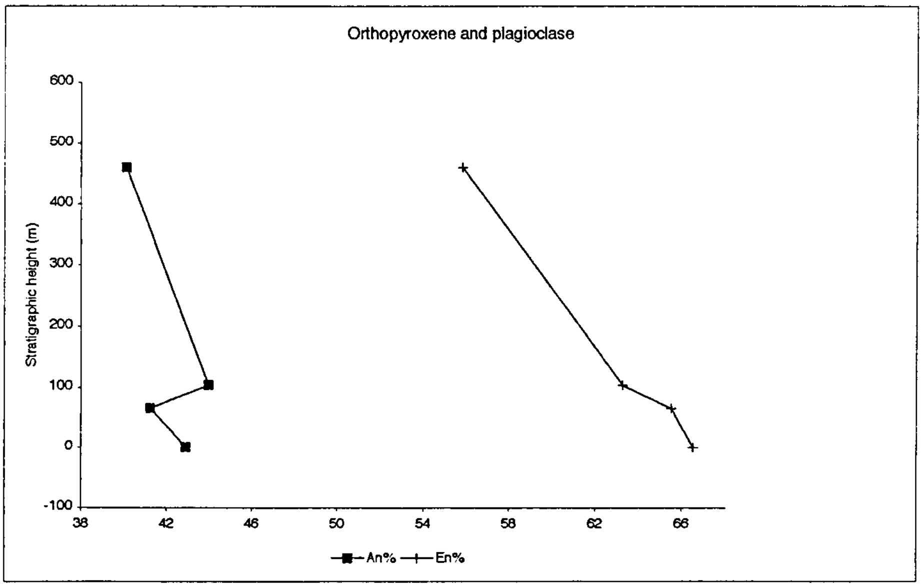


Fig. 5: Mineral composition versus stratigraphic heigt at the Bakka area. Abbreviations: ilm. = ilmenite, An = anorthite, En = enstatite.

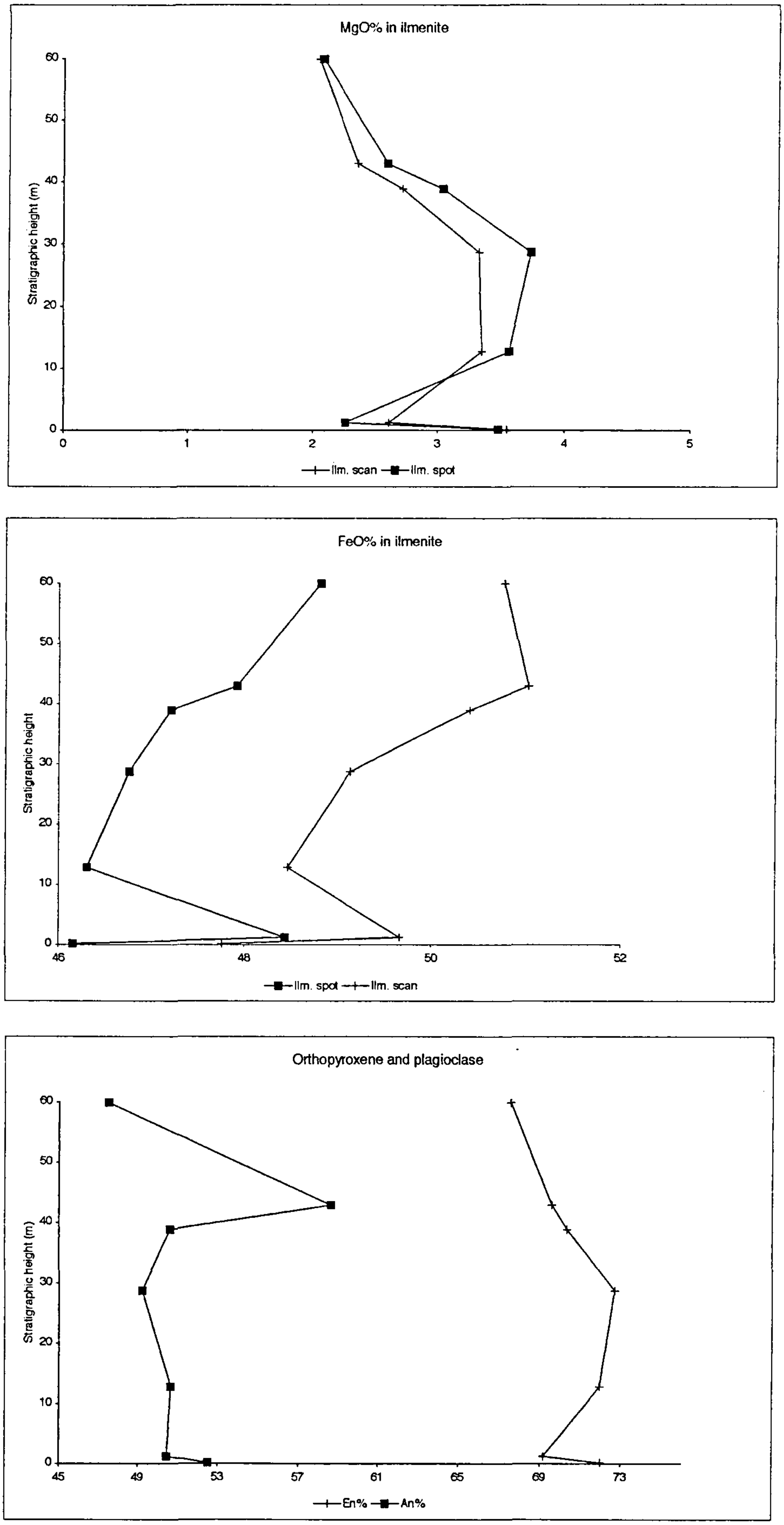


Fig. 6: Mineral composition versus stratigraphic heigt at Storgangen. Abbreviations: ilm. = ilmenite, An = anorthite, En = enstatite.

XRF field measurements

An XRF field survey was carried out on Fe-Ti oxide mineralisations in the southern part of the Bjerkreim-Sokndal layered intrusion using a portable XRF analyser (X-Met 880) developed by Outokompo OY. The standard samples, provided by Titania A/S, consisted of a set of crude ore, concentrates and waste from mine production at Tellnes and were chosen to give a maximum compositional span in Ti and Fe values. During the X-Met survey magnetic susceptibility and dip and strike of magmatic layering together with information about the width of the individual layers, character of mineralisation, host lithology, weathering conditions, etc. of the Fe-Ti oxide zones were also investigated.

With the X-Met instrument circular «points» with diameter ca. 2.0 cm are measured. Because the X-ray penetration into the rock is very limited it is necessary to avoid rusty surfaces, but the surface doesn't need to be fresh. It is possible to measure on a strongly weathered surface provided the mineral distribution is the same as in fresh outcrop (this was often the case in the Mydland area where both fresh and totally earth-weathered rock exist together).

The quality of the X-Met measurements has been tested by routine during the work and found to be good (see discussion in Nilsson & Staw 1996).

Presentation of the X-Met TiO_2 and Fe_{total} measurements

A total of 686 measurements distributed on 114 locations, averaging 6 measurements per location, were made. The measuring density varied from only one in oxide poor norite up to 34 in the single richest and widest Fe-Ti mineralised layer. The data collected were drawn on 5 sheet of 1:5000 scale economic maps (average TiO_2 and Fe values for each location measured). Furthermore, the data were plotted in scatter-diagrams. In the present report TiO_2 vs. Fe-total are plotted in Fig. 7 for all measured locations together with two areas that so far are considered to be the most interesting follow-up areas, Bakka and Mydland.

The diagrams show a distinct positive correlation between TiO_2 and Fe_{total} for the overall majority of points measured. The plots suggest that there is a strong correlation between ilmenite and magnetite in the oxide zones measured. We have not however yet been able to quantify this correlation as both orthopyroxene and clinopyroxene make up a substantial part of the silicate mass in the mineralised rocks.

Evaluation of the Fe-Ti potential based on X-Met-measurements

The following evaluation/judgement of areas covered in this survey is based on field observations, field measurements, lab analyses, the helicopter magnetic map, etc.

1. Most promising areas

Bakka area

The Bakka area has certain very good qualities. In a long roadcut NE of the Bakka farms parts of a thick Fe-Ti enriched layered zone with individual oxide rich layers up to more than 2.5 meter in width occur. X-Met measurements (Fig. 7) showed in average 9.09 % TiO_2 and 18.78 % Fe for seven locations measured across this zone. There also exist extensive Fe-Ti mineralised zones in roadcuts along most of the lower half of the road uphill to the farms Brandsberg, Skjevrås and Krune (TiO_2: 10.60 % and Fe: 20.21 % in average). Near the top of the road, near the Skjevrås farm a 10 to 12 meter wide and rich oxide zone is exposed in roadcut (average values measured: 11.75 % TiO_2 and 23.17 % Fe). On the other side of the Bakka-Åna (=Bakka river) oxide-rich zones were met with along the road uphill to the farms Steinbergslåtten and Herveland (averaging 8.54 % TiO_2 and 16.20 % Fe). In a roadcut just north of the camping place the very high average values 16.58 % TiO_2 and 19.95 % Fe were obtained. Conclusively, there are rich oxide zones in the Bakka area, but the zones are somewhat scattered. The terrain (topography) is mostly rough and partly extensively overburdened by scree, dense spruce plantations, etc. Therefore it is not easy to make correlation work of the individual oxide zones in this area. So far nearly all the work has been concentrated on roadcuts in this area.

Mydland area

Contrary to the Bakka area the Mydland area is flat agricultural land with very few outcrops. The area is characterised by much fine-scale layering (5-10 cm wide layers only) and relatively low TiO_2 and Fe values (in average 7.40 % TiO_2 and 17.48 % Fe for totally 15 locations measured in the oxide rich zone, see Fig. 7). The perhaps most promising feature at Mydland is a fairly large and very strong positive magnetic anomaly covering the area where Fe-Ti mineralisation has been encountered in small outcrops. There is a distinct conformity between the form and direction of the anomaly and the strike direction of the igneous layering within the different parts of the anomaly (SW strike in the western part of the anomaly, W strike in the central part of the anomaly and again SW strike in the NE end of the anomaly). Though the grades measured at Mydland are lower than those at Bakka, the mineralised outcrops at Mydland are very similar in several respects such as fine-scale modal layering and the average level of the Fe and Ti grades. If all these outcrops are added together to one single large mineralised zone, they define a width of 100 to 150 meters inside a strike length of 1 km. The validity of such an interpolation can easily be checked by ground magnetic profiles across the anomaly. This should be carried out where there are very few spruce plantations and practically no topographical obstacles.

2. Second priority areas

Rosslandsåna-Lindland-Bø utmark-Prestbro

This is the southern continuation of the Bakka zone, but not of the investigated locations here can match the Bakka locations in size and grades. However, in the southern part the overburden is extensive, the outcrops poor, and the anomaly very strong (Bø utmark, i. e. in the area Frøyland - Dognebakka). This part of the zone should not be rejected, but be evaluated together with Bakka and Mydland. A new housing estate in the central to western part of the anomaly and a churchyard in the SE flank of it are of course negative factors. In the northern part of the anomaly the area conflict seems to be less severe, but the anomaly is here somewhat weaker and narrower.

Ytra Bakkatjørna-Ørsland-Hølen

This is a Fe-Ti enriched zone in layered norite above the Bakka zone, and below Duchesne's «Transition Zone» (TZ) between the norite and the overlying mangerite. Along the northern side of the Ytra Bakkatjørna (tarn) and northwards on the land of the Ørsland farms the observed widths of the individual Fe-Ti oxide layers are only in the range 20 cm to 1 meter, but farther north where the river widens into the small lake Hølen, the mineralised zone is extensive and resembles the mineralisation type observed at Mydland.

Ørsland-Steinbergslåtten

Ørsland-Steinbergslåtten is exclusively thought as the ultramafic, Fe-Ti oxide enriched norite-mangerite «Transition Zone» (TZ) as described by Duchesne et al. (1987). The richest and widest locations within this zone were found along Profile 1 of Duchesne (i.e. NE of the southern Ørsland farm) where individual mineralised layers of more than 4 meter in width occur. Northwards from this profile several oxide-rich horizons were observed, whereas south of Duchesne's Profile 1 virtually no single outcrop worth measuring on was observed (i.e. only poorly layered norite/leuco-norite was observed).

3. Third priority areas

These are areas visited and found to have only a poor potential or no potential at all for Fe-Ti oxides. These areas will only shortly be listed without any further comments (interested readers are referred to the X-Met report (Nilsson and Staw 1996)):
Hauge-Dragland area, Sjonaråsen-Bjørgan plateau, Barstad, Skarås, Årstadøyna, Sokno-Kjellandsåno river branching, Storafjellet SE of Kjelland, Årstad mine with close surroundings and Lauvås occurrence (the Lauvås occurrence was not visited and the information is taken from the literature).

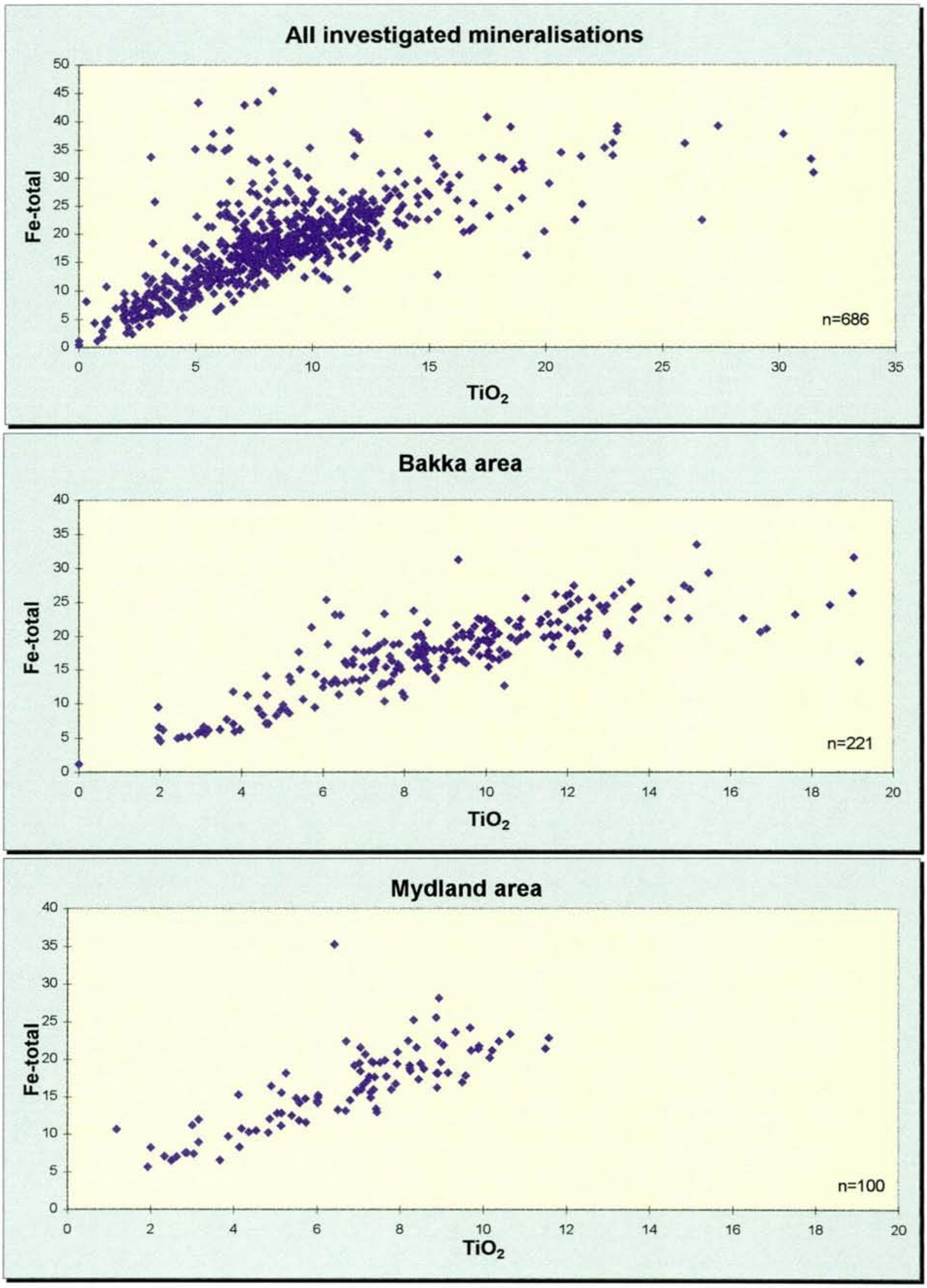


Fig. 7: Variations in TiO$_2$ versus Fe-total from X-Met measurements. NB! different scales. From Nilsson & Staw (1996).

MgO-content in ilmenite from the Tellnes deposit

Kullerud & Bjørlykke (1993) found a method to calculate the MgO-content in ilmenite from chemical analyses of the ore. To use the method it was necessary to make corrections for the content of non-ilmenite-minerals (silicates) in the concentrate. These corrections supposed that the composition of the non-ilmenite minerals were constant. Rolfsen (1994) found that there are large variations in the composition of the silicate minerals in the ore.

The present work by Kullerud (1996) focuses on the variations in the chemical composition of the silicates in the ore relative to the chemical variations in its bulk-analyses.
Kullerud (1996) concluded that silicate- and oxide-minerals show relative large chemical variations, especially with respect to the contents of Fe and Mg.
Based on statistical analyses of ore-analyses and mineral-analyses a set of equations were made to calculate the chemical composition of minerals in a sample when bulk chemistry is known. Another statistical calculation was made in order to find out if olivine is present in the sample. Both these calculations make it possible to take account for variations in mineral-content and mineral compositions when corrections of analyses of ilmenite concentrates are done.
An analysis was also made in order to decide how the MgO-content in ilmenite varies as a function of the chemical composition of the ore. The resulting equation is an improved version of an equation given by Kullerud & Bjørlykke (1993).

Chemical variations of the Tellnes ore

Kullerud & Bjørlykke (1993) investigated the chemical variations of the Tellnes ore. The ore body was shown to be chemical zoned. TiO_2 is enriched in the central parts and decreases gradually towards the hangingwall and the footwall. P_2O_5, S, and Cr show different zoning patterns. The content of TiO_2 is commonly in the range 10 - 25 %, but locally up to 35 %.

Plots of elements against TiO_2-content show two different trends: 1. high TiO_2-trend, 2. low TiO_2-trend. The two trends are especially easy to see on MgO-TiO_2-plots (Kullerud 1996).
In the high TiO_2-trend MgO decreases from 8 to 4 Wt% at a slightly increasing TiO_2-content. At the low TiO_2-trend, the TiO_2 content decreases from 20 to below 10 Wt% while MgO increases slightly.
The chemical variations are clearly related to the geometry of the ore. Cr - which is an important element while discussing ore quality - is commonly in the range 200 - 800 ppm, and increases when the content of ilmenite increases. V is also important when it comes to ore composition, and is usually in the range 0 - 1200 ppm. In general it shows a very pronounced trend plotted against TiO_2 and it increases while TiO_2 increases.

Based on the chemical variations in the drill holes the Tellnes ore body is subdivided into 4 zones (Fig. 8):

1) Upper marginal zone
    - generally high MgO-content, increasing TiO_2-content towards depth
2) Upper central zone
    - high MgO- and TiO_2-content
3) Lower central zone
    - Low MgO-, high TiO_2-content
4) Lower marginal zone
    - decreasing TiO_2-content, slightly increasing MgO-content

Mineralogical variations of the Tellnes ore

The main minerals of the Tellnes ore are *plagioclase, ilmenite, biotite, clinopyroxene, and orthopyroxene*. *Olivine* occurs as a main mineral in the upper central zone, but is absent in the lower parts. *Amphibole* occurs in a wider area of the ore than does olivine, but is usually not present in the lower marginal zone. Green *spinel* is common as an accessory, but not in the lower marginal zone. *Apatite, magnetite* and *Fe-, Ni-, Cu- and Co-sulphides* occur as accessories through the entire ore.

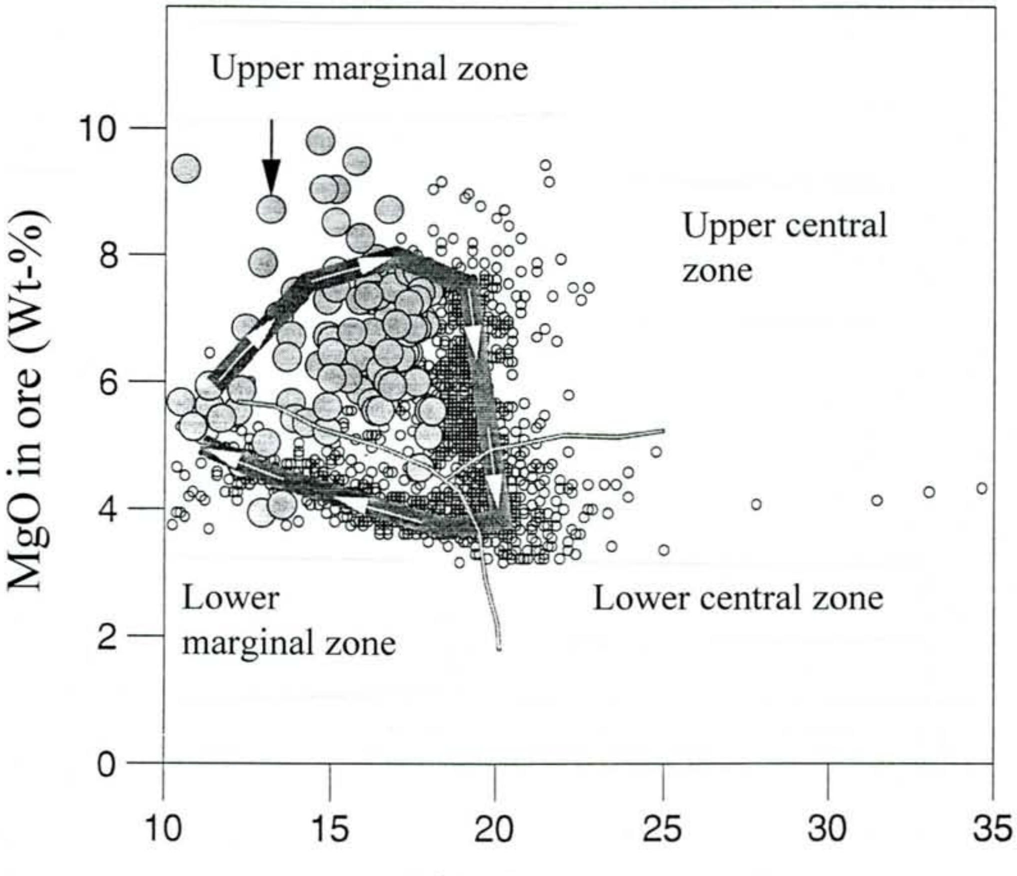


Fig. 8: 4 distinguished zones of the Tellnes ore. From Kullerud (1996).

Helicopter geophysics

The helicopter-borne geophysical measurements include the following methods (Rønning 1995):

- Magnetometry (total field & vertical gradient)
- Apparent resistivity
- VLF-EM (line & ortho)
- Radiometry (total, potassium, uranium, thorium)

The measurements were carried out along E-W-profiles with a distance of 100 metres between the lines. The geophysical data provide information that can either be applied directly in the prospecting for new ilmenite-magnetite mineralisations (magnetic total field, magnetic vertical gradient, apparent resistivity) or indirectly by solving more general geological problems (magnetic maps, VLF-EM maps, radiometric maps).

The *aeromagnetic total field map* (Fig. 9) can be divided neatly into regions of high positive magnetic intensity over the norites and mangerites of the Bjerkreim-Sokndal lopolith and regions of negative magnetic intensity over the Åna-Sira and Håland anorthosites. Magnetite-ilmenite-rich zones in the norite are indicated by positive anomalies. An example is the Mydland area. Positive magnetic anomalies at Mydland and Heskestad are also accompanied by strong negative anomalies in the south-eastern parts.

Positive magnetic anomalies are also present in the Bakka-Sokndal area where abundant thin Fe-Ti - mineralised zones occur. The individual zones are however impossible/difficult to distinguish. There appears to be several reasons for this: 1. Low thickness of the mineralised zones 2. The volume of variably oxide impregnated norite is much larger than the volume of the mineralised zones. 3. Different altitudes of the helicopter during measurements. - There is a positive correlation between the remanent magnetic intensity and topography due to the inability to drape perfectly the flight lines in this topographically steep region.
Mineralised zones occurring within the anorthosite, such as the Tellnes- and Storgangen ore bodies and the Bøstølen/Blåfjell area, are complicated and need further interpretation.

On the *magnetic vertical gradient map* several of the positive magnetic anomalies that indicate mineralisations are enhanced, especially those in the Hauge-Sokndal area were continuous anomalies can be traced for more than 3 km in the north-south direction.

On the *apparent resistivity map* there are many anomalies with less resistivity than normal. Except for those anomalies that are caused by lakes or bottom sediments they seem to be comparable to the magnetic anomalies in the norite. Thus, they might indicate magnetite/ilmenite/hematite-mineralisations. It is interesting to see that parts of the Tellnes ore body causes anomalies on this map. But, in general, it remains to be seen how many of the apparent resistivity anomalies can be correlated with water and marsh areas.

On the *radiometric maps* some of the rocks that are not associated with the mineralisations give strong anomalies; the mangeritic rocks have strong positive *K*-anomalies due to their K-feldspar content, while some of the rocks of the metamorphic envelope have strong positive *Th*-anomalies. As expected, the anorthositic massif shows very low radiometric radiation.

The *VLF-EM map* seems so far not to provide any large contribution to the prospecting, but they show some lineaments that probably will add information to the structural geology.

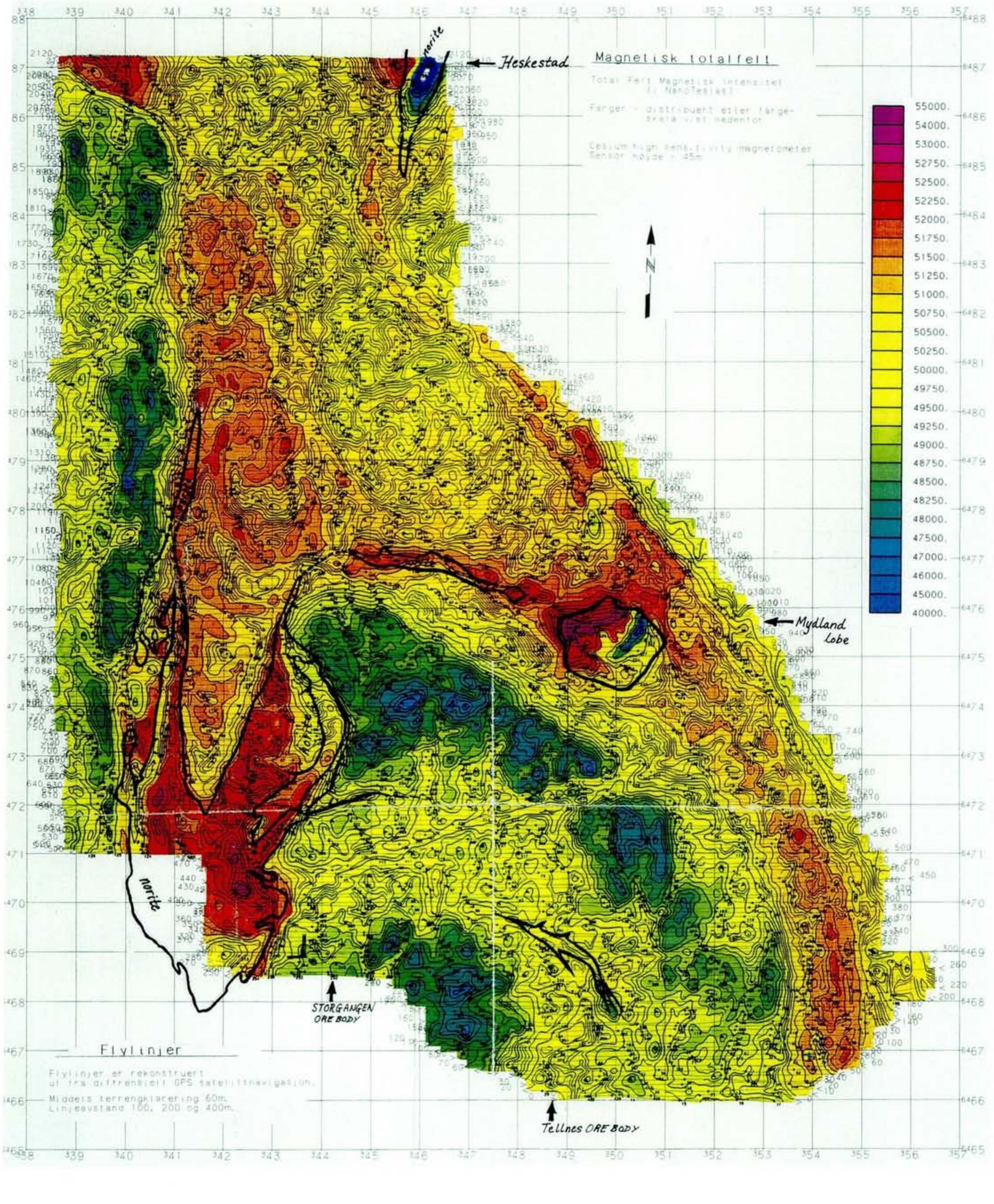


Fig. 9: Magnetic total field map (from Rønning 1995) showing the relation between anomalies and known oxide occurrences. In general, the negative anomalies are situated within anorthosite, while the most positive anomalies are situated within norite.

Petrophysics

The quest for a better understanding of the aeromagnetic maps led S.McEnroe and P. Robinson to initiate a rock-magnetic and paleomagnetic sampling program in the summer of 1995. The program was completed by L.P. Nilsson and H. Schiellerup during the next few months. The samples were then investigated by McEnroe to obtain information on several petrophysical aspects such as (McEnroe 1996):

1. Magnetic susceptibility
2. Natural remanent magnetism (NRM)
3. Q-value (the ratio between susceptibility and NRM
4. Orientation of NRM
5. Induced remanent magnetisation (IRM) and demagnetisation of induced remanent magnetisation
6. Characteristics of magnetic mineralogy
7. The relation between mineral composition and magnetic properties

The first 5 points influence directly on the outlook of the aeromagnetic maps, while the two latter points seek to find the mineralogical reasons for the obtained anomalies.
Some of her results are given below.

Magnetic susceptibility

Magnetic susceptibility is the capacity of the sample to acquire magnetisation. The magnetisation is induced by the applied field (geomagnetic field). The induced magnetisation of a rock primarily depends on susceptibility of the rock unless remanent magnetisation is playing a role. Magnetite is the only mineral that has a high susceptibility, and there is a positive correlation between content of magnetite and susceptibility. Variation in susceptibility is a function of mineralogy, magnetite versus hematite, and amount of oxide present in the sample.

Natural remanent magnetisation (NRM)

The natural remanent magnetisation (NRM) is the summation of all the components of magnetisation acquired, both primary and secondary. The *declination*, as measured in a sample, is the angle between true north and the horizontal component of the magnetic field vector. The *inclination* is the angle from the horizontal plane to the magnetic vector as measured in the vertical plane. The *intensity* of magnetisation *J*, is the measure of pole strength per unit area (A/m).

It is common that NRM plays a significant role in areas containing ilmenite-bearing ores such as the present study area.

Q-value

The Q value, which is the ratio between remanents and susceptibility, is a useful guide to the type of aeromagnetic anomaly to be expected.

A Q value < 1 indicates the samples are contributing mainly to the induced field. A Q value > 1 indicates the NRM is greater than the induced magnetisation and is playing a role. A Q value > 10 indicates that NRM is the dominant component of the aeromagnetic signature of the body. When Q is greater than 1 the direction of the NRM must be known to understand and model the anomaly.

Petrophysical explanation of the different anomalies

Overall features

It has been made obvious that the investigated area contains rocks with very high magnetic susceptibility and low remanents giving rise to large positive induced aeromagnetic anomalies such as within the norite complexes, and it also contains rocks with very strong reversed remanent magnetisation giving rise to large negative magnetic anomalies as in the anorthosites (Fig. 9).
Some examples of petrophysical values are given in Table 3. The general high remanents in the rocks is indicated by the high Q-values (McEnroe 1996). In most of the rocks which contain ilmenite with hematite exsolution, and magnetite-ilmenite and/or hematite/ilmenite lamellae in the pyroxenes, the Q-value is greater than 1. These rocks produce the aeromagnetic lows as at Heskestad and Mydland and part of the Tellnes mine.

Locality	Declin.	Inclin.	Intens.	Suscept. (10^{-3})	Q-value
Tellnes quarry	W	÷5 - ÷86	7	29	1-21
Sandbakk	Dispersed	+ ÷	39	213	3.5
Mydland, pos. magn. anomaly	NE	52	5	181	0.6
Mydland, neg. magnetic anomaly	SW, SE	÷ (steep)	8	33	6
Heskestad, pos. magn. anomaly	Dispersed	+÷	5	69	1.4
Heskestad, neg. magn. anomaly	Dispersed	÷	22	92	5
Bakka, pos. magn. anomaly	SW	+÷	10.3	231- 378	0.8
Åna-Sira anorthosite, neg. magn. anomaly	Dispersed	÷	5.5	3	14-102

Table 3: A few examples of petrophysical values from the investigated area. Large parts of the area have high Q-values and therefore high remanens. (Extracted from McEnroe 1996).

Mydland

Anomaly: Positive & negative
Rocks at the positive magnetic anomaly have low Q-values and high susceptibilities. The influence from NRM is low. Rocks from the associated negative anomaly has significantly higher Q-values and NRM. This means that the contribution from the NRM is significant.

Heskestad
Anomaly: Positive & negative
Rocks from the positive magnetic anomaly have relatively low susceptibilities, but the influence from NRM is rather low mainly because of its dispersed directions and low intensity.
In the samples from the associated negative anomaly the NRM intensity is distinctly higher and the inclination is negative. This means that the contribution from NRM is significant.

Sandbekk
Anomaly: neutral
The general high susceptibility is «overprinted» by high intensity NRM-values.

Bakka
Anomaly: positive
High susceptibility (up to 378 x 10^{-3}) and low Q-value (0.8) give a positive magnetic anomaly in this area.

Tellnes quarry
Anomaly: Weakly positive, almost neutral
High Q-values clearly influence the magnetic signature. Negative inclined NRM dominates and the Tellnes ore body therefore gives only a weak anomaly.

Åna-Sira anorthosite
Anomaly: large parts are negative
Very low susceptibility coupled with high remanens values lead to strong negative anomalies. This is in accordance with the negative correlation between magnetic intensity and topography.

Ilmenite chemistry

McEnroe (1996) made petrographical and mineral chemical analyses to be able to explain the petrophysical variations. Some of her results influence on the quality of the deposits, and such data are given below. It is important to note that different standarisation methods in McEnroe's and Schiellerup's micro probe analyses.

Tellnes mine area
Investigated samples from the Tellnes ore have maximum contents of MgO and Cr_2O_3 in ilmenite of 4.5 % and 0.27 % respectively (Figs. 10 & 11). Plots of Wt% MgO versus Wt% TiO_2 in ilmenite (Fig. 11) show an array of composition that is the result of four different processes;
A) Variation in the bulk composition of primary ilmenite as a result of magmatic processes
B) Composition variation as a result of analyses in which an attempt was made to analyse hematite exsolution lamellae in ilmenite
C) Compositions produced by secondary reactions between ilmenite and magnetite, commonly producing spinel-bearing reaction symplectites or with sulfides
D) Ilmenite exsolution lamellae in pyroxene grains

Concerning the first process McEnroe concludes that there is a chemical progression from hematite-rich composition to hematite-poor composition. The progression is reflected by (a) content of significant amounts of magnetite and of oxide exsolution in the hematite-poor ilmenite sample, (b) decreasing MgO and Cr_2O_3 in ilmenite from hematite-rich to hematite-poor samples, and (c) increasing Fe/Mg + Fe in pyroxene. The Cr_2O_3-trend is explained by concentration of Cr in the eskolaite component in the hematite exsolution lamellae.

Oxide cumulate norite in the Bakka area

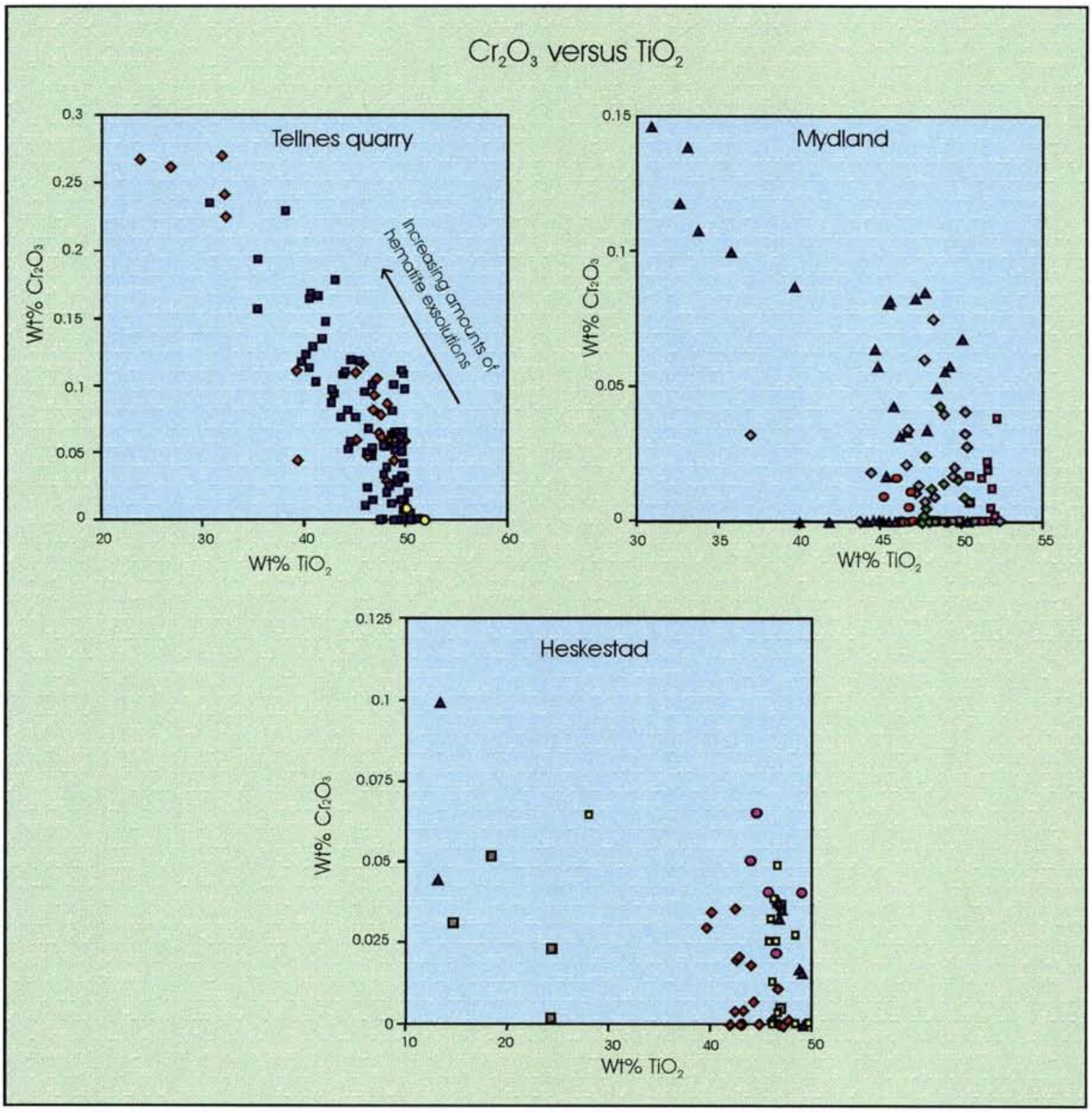
A small range of Ti indicates limited, if any, exsolution of hematite lamellae. A trend with variable MgO content (~ 0.6 - 2.1 %) within the range 49-52 % TiO_2 is observed. This is clearly different from the trends in samples produced by hematite exsolution. There is no consistent relationship between Cr and Ti-content such as that shown in samples with hematite lamellae, and Cr_2O_3 values are mostly very close to the detection limit. However, a few analyses give up to ~ 0.07 Wt % Cr_2O_3.

Oxide cumulate norite in the Mydland area

The maximum amount of MgO and Cr_2O_3 in ilmenite in the analysed samples is 1.75 % and 0.15 % respectively (Figs. 10 & 11), which is substantially lower than in the samples from the Tellnes quarry (4.5 % MgO and 0.27 % Cr_2O_3). Analyses that give high TiO_2 - values are from a sample where Ti-rich ilmenite coexists with magnetite and where hematite lamellae is absent. Otherwise, hematite lamellae is present in very small amounts in three samples, while they are more abundant in the two remaining samples. One of the thin sections indicate a trend of gradually decreasing MgO with decreasing TiO_2 consistent with hematite exsolution and a much lower MgO group of ilmenite exsolutions in magnetite. Low Ti analyses are also richest in Cr_2O_3 suggesting incorporation of an eskolaite component into the exsolving hematite, but a number of low-Ti low-Cr analyses make this interpretation questionable. Very few analyses contain significant Al, and those that do may be due to small spinel lamellae.

Oxide Cumulate Norites in the Heskestad Area

The maximum amounts of MgO and Cr_2O_3 in ilmenite in the analysed samples are 1.1% and 0.1% respectively (Figs. 10 & 11). Many of the samples appear to lack hematite exsolution and they contain less than 0.5 weight % MgO. A few low analyses of TiO_2 represent points including abundant hematite exsolution lamellae. These analyses are also lower in MgO than the Ti-rich ilmenite in the same sample. The other samples appear to lack hematite exsolution and they contain less than 0.5 weight % MgO. Low Ti analyses are generally richer in Cr_2O_3 than the high-Ti analyses in the same sample, suggesting incorporation of an eskolaite component into the exsolving hematite, but several low-Ti low-Cr analyses make this interpretation questionable. Grains apparently lacking hematite exsolution locally have as high or higher Cr. Very few analyses contain significant Al, but the lowest Ti analyses are richer in Al, possibly explained by a corundum component in ilmenite. Plots of V_2O_5 versus TiO_2 from Heskestad samples and from Mydland samples show that is a low V_2O_5 content when the TiO_2 content is high (poor ilmenite) and visa versa. This indicates that there is a V_2O_5 component in the exsolved hematite.



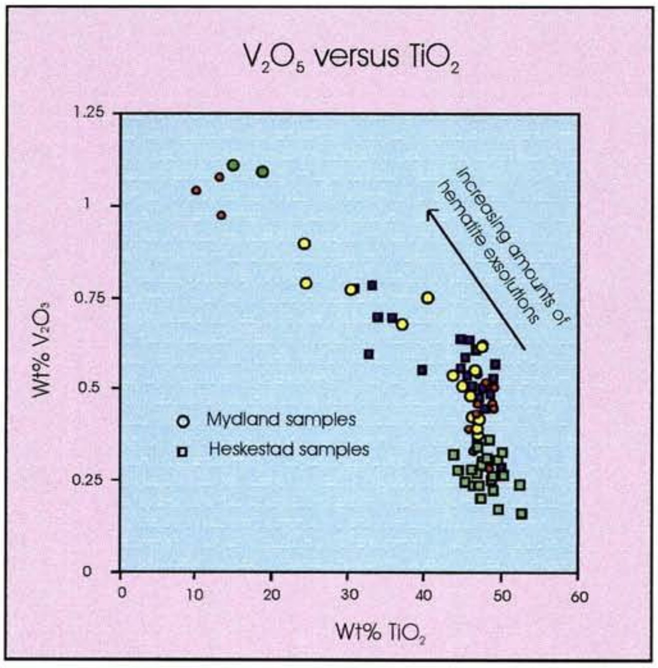


Fig. 10: V_2O_5 *and* Cr_2O_3 *versus* TiO_2 *in ilmenite. The different samples are distinguished by colours. Only some areas are included. More details are given by McEnroe (1996).*

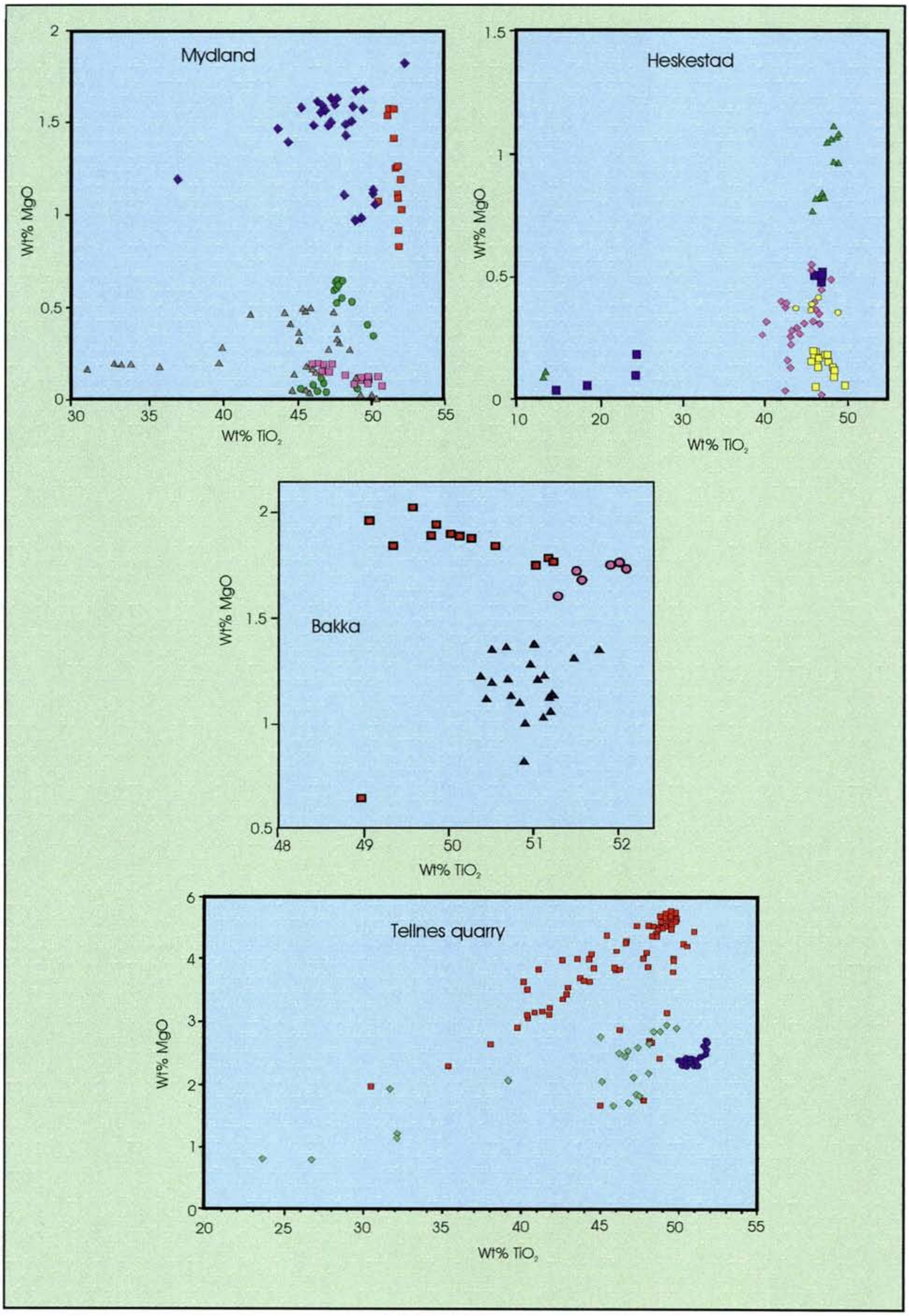


Fig. 11: MgO-TiO$_2$-plots of ilmenites. Different samples are distinguished by symbols (from McEnroe 1996).

Gravimetrical measurements on Tellnes

Gravimetric measurements were carried out at the Tellnes ore body (Mauring & Gellein 1995). The object was to map the ore towards depth at the eastern part of the quarry and to map an eventually south-eastern continuation of the ore. Four profiles across the ore body were measured and modelled. Good terrain corrections were difficult to achieve due to the extreme topography. Interpretation of one of the profiles yielded the result that the ore continues towards south at a depth of 75 metres. The ore body was interpreted to have a dip around 60° and to be around 100 metres thick.

SUMMARY

The current research on ilmenite in the Egersund anorthositic Province have been summarised in the present report. The first step in the prospecting for new ilmenite deposits is considered to be finished. This step contains primarily collection of raw data, such as airborne geophysical measurements, petrophysical studies, some recognisance mapping, X-Met-measurements, as well as some thin section studies and microprobe analyses. In addition, more specialised studies like gravimetry and detailed geochemical studies have been applied to the Tellnes deposit. The most promising Fe-Ti -occurrences are so far found to be those at Bakka and Mydland. Both contain ilmenite with favourable low amounts of Cr_2O_3 and MgO and very little or no hematite exsolution lamellae. Several of the airborne geophysical maps produced show interesting positive and negative anomalies that can be used either in the prospecting and mapping of magnetite/ilmenite occurrences or in the mapping of large scale geological structures. The magnetic maps show many interesting positive anomalies associated with Fe-Ti mineralised norites. Petrophysical studies have shown that the Egersund anorthositic Province has unusually high values of remanent magnetism that cause negative magnetic anomalies in parts of the area.

In the next step of the investigation it is necessary to concentrate on 1) mapping the areas of interest, 2) continue the work that provide a better understanding of the relationship between data obtained from whole rock chemistry, mineral chemistry and petrography, and 3) continue the petrophysical work in order to be able to make 3D interpretations of geophysical maps.

SUGGESTIONS FOR FURTHER WORK

Suggested work for 1996 is as follows:

- Mapping and correlation of mineralisations at the known locations at the Bakka-Hauge and Mydland areas, as well as other interesting known deposits and interesting areas indicated by geophysics
    - Special equipment: X-Met, magnetometer
    - Air photo interpretation
    - Digitizing previous work. Together with topographical and geophysical maps it makes the basis of the prospecting
    - The goal for this work is to be able to produce maps at all scales from detailed maps of deposits to overview maps

- Establish a better understanding of the relationship between the data obtained from whole rock chemistry, mineral chemistry and petrography
    - XRF-field - measurements, thin section studies, picture imaging, microprobe, whole-rock chemistry
- Continue the petrophysical work to be able to do 3D-interpreation of mineralised zones
- Combined interpretations of geophysical and geological maps
- Compile data from the entire Egersund anorthositic Province
- Make recognisance mapping in the northern part of the Bjerkreim-Sokndal lopolith

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Electron micro probe analysis', Feb 1996.

ILMENITE, SPOT

SAMPLE	SiO2	TiO2	Al2O3	FeO	MnO	MgO	Cr2O3	NiO	V2O5	SUM
ST84-1	0,17	49,42	0,17	46,16	0,46	3,48	0,01	0,01	0,29	100,17
ST84-2	0,16	48,95	0,16	48,43	0,44	2,27	0,02	0,03	0,25	100,72
ST84-6	0,23	49,54	0,24	46,31	0,55	3,56	0,01	0,01	0,16	100,61
ST84-8	0,24	49,83	0,22	46,77	0,42	3,74	0,01	0,02	0,10	101,34
ST84-10	0,14	49,48	0,16	47,21	0,47	3,04	0,02	0,02	0,25	100,79
ST84-12	0,19	49,39	0,19	47,92	0,49	2,60	0,02	0,01	0,23	101,04
ST84-14	0,17	48,67	0,21	48,81	0,40	2,08	0,02	0,01	0,24	100,61
1006.06.11	0,26	49,22	0,20	46,83	0,49	3,59	0,07	0,03	0,16	100,85
1006.03.8	0,17	51,85	0,21	45,82	0,51	2,52	0,00	0,01	0,09	101,20
1006.03.3	0,16	51,10	0,16	46,45	0,59	2,48	0,00	0,01	0,14	101,08
1006.03.1	0,16	48,69	0,24	49,34	0,59	0,98	0,01	0,00	0,09	100,10
1006.03.11	0,18	47,23	0,15	51,13	0,76	0,09	0,01	0,01	0,17	99,74
1002.01.1	0,11	51,78	0,17	46,74	0,76	1,40	0,00	0,01	0,04	101,00
1002.01.2	0,13	48,68	0,16	48,49	0,51	2,16	0,01	0,00	0,18	100,34
1007.01.1	0,18	50,12	0,22	44,81	0,59	4,20	0,11	0,04	0,13	100,40

ILMENITE, WHOLE GRAIN

SAMPLE	SiO2	TiO2	Al2O3	FeO	MnO	MgO	Cr2O3	NiO	V2O5	SUM
ST84-1	0,61	46,12	0,35	47,77	0,48	3,55	0,01	0,02	0,31	99,21
ST84-2	1,12	44,91	0,26	49,67	0,50	2,61	0,01	0,01	0,31	99,40
ST84-6	0,08	46,06	0,20	48,46	0,35	3,35	0,01	0,01	0,33	98,86
ST84-8	0,15	46,18	0,19	49,13	0,36	3,33	0,01	0,02	0,26	99,63
ST84-10	0,22	44,79	0,23	50,40	0,58	2,72	0,01	0,00	0,30	99,26
ST84-12	0,23	44,91	0,22	51,02	0,38	2,36	0,00	0,01	0,30	99,43
ST84-14	0,17	44,82	0,28	50,77	0,41	2,05	0,04	0,01	0,28	98,84
1006.06.11	0,29	48,17	0,24	46,08	0,38	3,40	0,07	0,02	0,32	98,96
1006.03.8	0,19	50,74	0,16	45,15	0,64	2,43	0,00	0,01	0,15	99,49
1006.03.3	0,24	50,02	0,18	46,46	0,58	2,32	0,00	0,00	0,14	99,94
1006.03.1	0,49	47,41	0,27	48,53	0,63	1,07	0,00	0,01	0,17	98,58
1006.03.11	0,39	47,34	0,31	50,62	0,69	0,32	0,01	0,00	0,23	99,91
1002.01.1	1,01	49,88	0,19	46,04	0,72	1,52	0,00	0,01	0,03	99,40
1002.01.2	0,24	46,25	0,28	49,44	0,47	2,13	0,01	0,00	0,24	99,06
1007.01.1	0,25	45,08	0,21	48,49	0,39	3,53	0,16	0,05	0,24	98,39

MAGNETITE

SAMPLE	SiO2	TiO2	Al2O3	FeO	MnO	MgO	Cr2O3	NiO	V2O5	SUM
ST84-1	0,21	0,00	0,62	91,80	0,33	0,30	0,08	0,02	0,79	94,16
ST84-2	0,35	0,00	0,36	92,50	0,10	0,04	0,11	0,06	0,75	94,27
ST84-6	0,24	0,00	0,58	91,54	0,40	0,34	0,10	0,02	0,68	93,91
ST84-8	0,19	0,00	0,54	92,65	0,37	0,30	0,12	0,03	0,77	94,97
ST84-10	0,23	0,00	0,50	92,19	0,34	0,10	0,18	0,04	0,66	94,24
ST84-12	0,25	0,00	0,49	92,96	0,20	0,11	0,09	0,02	0,72	94,85
1006.06.11	0,31	0,05	0,52	90,16	0,01	0,22	1,81	0,12	0,84	94,04
1006.03.8	0,21	4,65	1,54	86,52	0,27	0,31	0,01	0,01	1,00	94,54
1006.03.3	0,19	1,17	0,78	90,96	0,07	0,18	0,02	0,00	1,12	94,49
1006.03.1	0,24	0,20	0,75	92,70	0,28	0,09	0,01	0,01	0,95	95,22
1006.03.11	0,75	4,38	1,03	85,77	0,49	0,27	0,02	0,01	0,79	93,50
1002.01.1	1,17	4,89	2,45	84,78	0,28	0,23	0,00	0,00	0,25	94,07
1002.01.2	0,17	0,00	0,48	91,80	0,34	0,18	0,08	0,01	0,84	93,90

PLAGIOCLASE

SAMPLE	SiO2	TiO2	Al2O3	FeO	MnO	CaO	Na2O	K2O	SUM	An%
ST84-1	54,69	0,09	27,18	0,13	0,10	10,93	5,46	0,00	98,56	52,5
ST84-2	56,62	0,06	26,46	0,23	0,08	10,18	5,52	0,00	99,15	50,5
ST84-6	55,59	0,06	26,89	0,21	0,07	10,07	5,42	0,65	98,96	50,7
ST84-8	55,83	0,16	26,77	0,19	0,06	9,77	5,57	0,58	98,93	49,2
ST84-10	55,42	0,12	26,96	0,31	0,07	10,03	5,41	0,60	98,92	50,6
ST84-12	53,52	0,14	28,32	0,17	0,10	11,90	4,64	0,19	98,98	58,6
ST84-14	56,28	0,05	26,21	0,22	0,08	9,49	5,80	0,53	98,66	47,5
1006.06.11	56,71	0,09	25,95	0,17	0,07	9,09	6,05	0,64	98,77	45,3
1006.03.8	56,51	0,09	25,38	0,24	0,07	8,39	6,17	0,59	97,45	42,9
1006.03.3	56,92	0,06	25,22	0,15	0,02	8,09	6,37	0,73	97,56	41,2
1006.03.1	56,97	0,08	25,47	0,16	0,03	8,55	6,01	0,74	98,01	44,0
1006.03.11	58,60	0,03	24,95	0,22	0,19	7,85	6,48	0,37	98,69	40,1
1002.01.1	58,14	0,11	24,78	0,09	0,06	7,34	6,60	0,69	97,80	38,1
1002.01.2	56,88	0,06	25,75	0,18	0,00	8,67	6,17	0,35	98,05	43,7
1007.01.1	55,38	0,00	27,64	0,14	0,03	10,27	5,53	0,15	99,14	50,6

Appendix 1: Table of mineral chemistry from different localities (measured by H. Schiellerup). The difference between spot and whole grain analyses is explained in the text. Sample localities: ST84: Storgangen, 1002: Mydland, 1006.03: Bakka, 1006.06: Årstad, 1007: Florklev - Ålgård.

CA-POOR PYROXENE

SAMPLE	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	Cr2O3	SUM	En%
ST84-1	52,89	0,27	1,92	17,77	0,30	25,64	1,25	0,51	0,09	100,63	72,0
ST84-2	53,09	0,21	1,79	19,71	0,34	24,83	0,79	0,66	0,05	101,46	69,2
ST84-6	53,12	0,32	1,90	18,12	0,36	26,08	0,72	0,00	0,14	100,75	72,0
ST84-8	53,44	0,20	1,92	17,68	0,43	26,41	0,76	0,60	0,16	101,60	72,7
ST84-10	53,48	0,16	1,92	19,30	0,32	25,64	0,82	0,60	0,14	102,40	70,3
ST84-12	52,87	0,20	1,79	19,67	0,26	25,22	0,65	0,69	0,13	101,48	69,6
ST84-14	52,82	0,16	1,69	20,86	0,46	24,36	1,09	0,79	0,16	102,38	67,5
1006.06.11	53,62	0,22	2,08	16,36	0,24	27,50	0,65	0,59	0,04	101,29	75,0
1006.03.8	52,07	0,13	1,45	21,17	0,37	23,60	0,80	0,86	0,00	100,45	66,5
1006.03.3	52,06	0,19	1,43	21,64	0,43	23,09	1,02	0,78	0,00	100,63	65,5
1006.03.1	52,26	0,17	1,27	23,21	0,44	22,48	0,85	0,89	0,03	101,60	63,3
1006.03.11	51,42	0,04	0,97	27,62	0,61	19,60	0,85	1,05	0,03	102,18	55,9
1002.01.1	50,63	0,19	1,05	27,66	0,70	18,63	0,75	1,03	0,00	100,65	54,6
1002.01.2	52,71	0,19	1,48	21,26	0,46	23,70	1,09	0,71	0,00	101,59	66,5

CA-RICH PYROXENE

SAMPLE	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	Cr2O3	SUM	Mg#
1006.03.8	50,85	0,52	2,62	9,31	0,39	13,70	21,51	0,87	0,04	99,79	72,4
1006.03.3	50,93	0,45	2,37	10,21	0,22	13,43	21,57	0,91	0,04	100,12	70,1
1006.03.1	50,93	0,45	2,37	10,21	0,22	13,43	21,57	0,91	0,04	100,12	70,1
1006.03.11	51,19	0,44	1,79	11,59	0,23	12,67	21,93	0,98	0,04	100,85	66,1
1002.01.1	50,81	0,35	1,96	12,46	0,40	12,44	20,48	0,94	0,00	99,83	64,0

OLIVINE

SAMPLE	SiO2	Al2O3	FeO	MnO	MgO	SUM	Fo%
1006.06.11	38,92	0,00	22,65	0,33	39,40	101,30	75,6

BIOTITE

SAMPLE	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	SUM
ST84-14	38,45	4,07	14,00	6,62	0,32	20,54	0,05	0,2	9,02	93,25
1006.06.11	36,46	10,54	14,01	9,35	0,68	15,20	0,11	0,30	9,79	96,43
1006.03.3	36,81	8,14	13,56	11,57	0,10	15,77	0,14	0,64	9,85	96,59

CLORITE

SAMPLE	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	Cr2O3	SUM
1007.01.1	32,46	0,07	13,18	14,49	0,25	24,96	0,11	0,31	0,05	3,25	89,13

APATITE

SAMPLE	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	P2O5	SUM
1006.03.8	0,19	0,38	0,11	0,18	0,00	0,05	56,28	0,20	0,01	42,21	99,61

SPINEL

SAMPLE	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	Cr2O3	NiO	V2O5	ZnO	SUM
ST84-1 (grey)	0,50	0,93	40,81	47,64	0,14	11,57				0,13	0,05	0,38		102,14
1006.03.8 (grey)	0,28	0,44	58,74	19,95	0,30	11,14				0,01	0,00	0,04	3,39	94,30
1006.06.11 (green)	0,31	0,38	56,54	16,44	0,09	15,65	0,00	2,83	0,14	0,03	0,00	0,03	3,85	96,30
1006.06.11 (green)	0,21	0,26	56,42	16,31	0,05	13,09				1,89	0,14	0,02	3,31	91,70
1007.01.1 (green)	0,09	0,11	56,22	16,82	0,07	16,12	0,03	2,60	0,06	3,19	0,26	0,07	3,20	98,82