

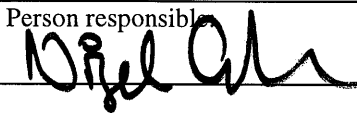
NGU Report 99.129

Rutile deposits in Norway. Vol 1: Text.

REPORT

Geological Survey of Norway
N-7441 Trondheim, Norway
Tel.: 47 73 90 40 11
Telefax 47 73 92 16 20



Report no.: 99.129		ISSN 0800-3416	Grading: Åpen
Title: Rutile deposits in Norway. Vol. 1: Text			
Authors: Korneliussen, A., Furuhaug., L., Gautneb, H. & Ihlen, P.		Client: Rio Tinto Iron & Titanium	
County: Norway		Commune:	
Map-sheet name (M=1:250.000)		Map-sheet no. and -name (M=1:50.000)	
Deposit name and grid-reference:		Number of pages: 61 Price (NOK): Kr. 85,- Map enclosures:	
Fieldwork carried out: 1989-94, 1999	Date of report: 14 Dec. 1999	Project no.: 284700	Person responsible: 
Summary: <p>Important rutile deposits in Norway are of two main types: eclogite rutile deposits in Western Norway and metasomatic rutile deposits in the Bamble province of southernmost Norway. Eclogite deposits formed by the metamorphic transformation of Proterozoic mafic rocks during Caledonian high-pressure metamorphism at 400 Ma. Rutile-bearing eclogites are found in various geological sub-provinces from the Bergen region in the south to the Kristiansund region in the north. The metasomatic rutile deposits, such as various rutile-bearing amphibolites and albitites in the Bamble geological province in southernmost Norway, formed by the metasomatic transformation of ilmenite-bearing gabbroic and amphibolitic rocks at approx. 1150 Ma.</p> <p>Based on a comparison of rutile deposits types, provinces and individual deposits, the northern part of the Førdefjord eclogite province in Sogn og Fjordane county seems to have the largest potential for economic rutile deposits. But also other eclogite areas, such as the Dalsfjord eclogite province, also in Sogn og Fjordane, and the Holsnøy area in Hordaland, are of significant interest and should be further investigated.</p> <p>Rutile from deposits in the Bamble province are uranium-bearing, which is a disadvantage compared to rutile from eclogite deposits that is practically free from this element. However, large areas in the Bamble province are more-or-less unexplored for rutile, and it is probably that significant new deposits could be identified by further exploration.</p>			
Keywords: Mineral resources	Rutile	eclogite	
Metamorphism	Metasomatism	albitite	
fagrapport			

CONTENTS

1. INTRODUCTION	4
2. SUMMARY	4
2.1. WORK DONE.....	4
2.2. RESULTS.....	5
2.3. SUGGESTIONS FOR FURTHER INVESTIGATION	6
3. CONFIDENTIALITY	8
4. THE GEOLOGIC PROVINCES	8
4.1. ECLOGITES OF W. NORWAY	8
4.2 THE BERGEN REGION	11
4.3 THE DALSFJORD REGION	12
4.4. THE FØRDEFJORD REGION	13
4.5 THE NORDFJORD REGION	15
4.6 THE ÅLESUND REGION	15
4.7 THE MOLDE REGION.....	16
4.8 THE KRISTIANSUND REGION.....	16
4.9 THE ROMSDAL REGION.....	16
4.10 OTHER ECLOGITE LOCALITIES	17
4.11 RUTILE-BEARING ROCKS IN THE BAMBLE REGION.....	17
4.12 THE ROGALAND ANORTHOSITE PROVINCE	20
5. THE ENGEBØFJELLET DEPOSIT.....	21
6. THE STEINKORSEN ECLOGITE.....	28
7. VARIATIONS IN OXIDE GRAIN-SIZE.....	31
8.1 IMAGE PROCESSING AND CHARACTERISATION OF THE TITANIUM MINERALS BASED ON OPTICAL IMAGES ...	31
8.2 IMAGE PROCESSING AND CHARACTERISATION OF TITANIUM MINERALS BASED ON SEM-IMAGES	33
8. ON THE VARIATION IN RUTILE GRAIN-SIZE	33
9. RUTILE MINERAL CHEMISTRY	38
10. RUTILE-FORMING HYDROTHERMAL SYSTEMS.....	38
11. MINERAL DEPOSITS ASSOCIATED WITH MESO-PROTEROZOIC NA-METASOMATISM IN SOUTHERN SCANDINAVIA.....	39
12. THE RUTILE DATABASE.....	42
13. DISCUSSION AND CONCLUSION	42
14. REFERENCES	47

1. INTRODUCTION

The purpose of the project is to identify significant rutile deposits. The goals within the first project year are to define favourable rutile resource situations/areas and evaluate the significance of a distinct gravity anomaly at Steinkorsen near Naustdal (see separate report by Dalsegg, 1999).

The main activity at this first stage of the project has been to compile information of rutile-bearing rocks and deposits of various types in Norway, and discuss the mineral resource possibilities in the respective areas. The focus has been on rutile-bearing eclogite rocks in West Norway, although rutile-bearing metasomatic rocks in the Bamble province of southernmost Norway and rutile-bearing rocks in the Rogaland anorthosite province are also included. Field-work has been done to obtain additional information in some areas, such as at the Steinkorsen locality in the Førdefjord region, and in parts of the Bamble, Rogaland and Oslo rift provinces. Information of the individual rutile occurrences is stored in a PC database.

A priority in this report is to characterise rutile deposits by combining geological maps, microphotographs, grain-size information and analytical data, and to visualise this information in figures.

Much of the information used is obtained by the NGU/DuPont/Conoco project in 1992-94, which is now open-file. Information obtained by that project after 1994 is still confidential. DuPont and Conoco have been informed of the existence of the Rio Tinto Iron & Titanium (RTIT) – NGU project. As a consequence of this communication, Conoco manager Jan Egeland at his own initiative informed that NGU is free to include geological information on the Engebøfjellet rutile/eclogite deposit in reports to RTIT.

The making of this report has been done approximately as planned, aimed to give a rough overview of the situation. The quality and the amount of details of the various parts of the report varies considerably. Particularly the database is incomplete in the way that text information for many deposits have not yet been put in. However, it is believed that the missing information will not change the overall impression and conclusions.

2. SUMMARY

2.1. Work done

- Field investigations have been done at the Steinkorsen (Naustdal) gravity anomaly, of hydrothermally altered anorthosites in the Proterozoic Rogaland anorthosite province, of various metasomatic rutile deposits in the Proterozoic Bamble province, and of hydrothermally altered larvikites (a range of rocks with monzonitic composition, often with distinct similarity to massice-type anorthosites) in the Permian Oslofjord area.
- Some field-localities and samples taken during the 1999 field-work have been photographed. These photographs are available in digital form.

- A variety of old thin-sections of rutile-bearing rocks, mainly eclogites, have been selected for microphotographing and grain-size image processing, and colour copies in A4 format have been made of the thin-sections. The microphotographs are available in digital form.
- Project information is available in a PC database exclusively made for this project. Based on this database, locality information is plotted in ArcView maps showing the geographic distribution of the localities, also distinguishing the various occurrences in categories based on importance. Updated versions of these maps can easily be printed out when new information is added into the database.

2.2. Results

- ***TiO₂-content.*** (1) A variety of metasomatic deposits in the Bamble district of southernmost Norway are TiO₂-rich (> 5 % TiO₂) locally, but average grades over large volumes of rock will in most cases be under 3 % TiO₂. Of those investigated only the Ødegård rutile deposit (Fig. 19) can be regarded as interesting for rutile, it contains 2-4 % rutile along a more than 1 km long zone. (2) Several of the eclogite deposits have > 3 % TiO₂, such as Husebø in the Bergen region, Orkheia, Ramsgrønova and Saurdal in the Dalsfjord region, and Fureviknipa, Engebøfjellet, Steinkorsen and the Naustdal village eclogite in the Førdefjord region. Of these deposits only Engebøfjellet has experienced significant core-drilling, and an ore resource of 400 Mt with 3-5 % rutile has been defined by DuPont/Conoco.
- ***Rutile vs. TiO₂.*** The rutile/TiO₂-ratio show significant variation between deposits as well as within deposits. Example of deposits in which more than 90% of the titanium occur in rutile are (1) Engebøfjellet from the Førdefjord region, (2) Orkheia, Drøsdal and Ramsgrønova from the Dalsfjord region, and (3) metasomatic deposits in the Bamble region, such as the Lindvikkollen albitite and the Ødegården hornblende-scapolite rock.
- ***Rutile grain-size.*** The oxide grain-size vary widely between deposits. Among those eclogites with a titanium-potential, the most fine-grained are eclogites found in the Førdefjord area, such as Engebøfjellet, Steinkorsen and the Naustdal village eclogite. Most other eclogites in W. Norway are distinctly more coarse-grained than those at Førdefjord.
- ***Uranium.*** Analyses of mineral separates have shown that rutile from eclogite is practically free of uranium (< 0.5 ppm U) while rutile from the metasomatic deposits tend to be distinctly U-enriched (> 50 ppm U).
- ***Calcium.*** Normally 0.2% CaO is the upper limit that is accepted by titanium pigment producers for titanium feedstocks for pigment production by the chlorination process. In most of the rutile separates analysed by NGU, the CaO-content is higher than the 0.2% limit, indicating that CaO would be a major problem in the beneficiation of these ores. An interesting observation is that the Engebøfjell eclogite deposit comes out with relatively low CaO-values in the rutile separates. Calcium is a major element in most silicate

minerals in both eclogites and in the metasomatic deposits. In some deposits titanite is present.

- **Geography.** This report does not focus on the geographic position of individual deposits. The distance from the sea for some deposits is, however, mentioned in Table 6, while their overall geographic position is shown by the various maps in this report. The road-map (Appendix 12) give a rough indication of the population density and the infrastructure in the respective areas. In general, most of the deposits that are mentioned in this report, have a good position in relation to infrastructure. Environmental conflicts in case of mining, cannot be avoided any place in Norway, but will vary significantly from area to area.
- **Mineral resources.** The Vevring – Naustdal area on the northern side of Førdefjord, which includes the Engebøfjellet and Steinkorsen eclogite deposits as well as the Naustdal village eclogite, represent the largest rutile resource potential known in Norway. At Engebøfjellet alone roughly 400 Mt. of 3-5% rutile ore have been identified by DuPont-Conoco. Due to the size of the Steinkorsen gravity anomaly, this deposit might also contain several hundred Mt of ore. All in all the rutile ore resources in this area might reach 1000 Mt (proven + probable ore). With an estimated average rutile grade of 4 %, the resource potential of rutile would be approx. 40 Mt of rutile of which 50% is recoverable by present beneficiation techniques. This represent a large portion of the world's resources of rutile.
- It is probable that additional, significant resources can be identified in the Dalsfjord region and in the Holsnøy area of the Bergen region.
- In the Bamble region the Ødegård deposit might represent a significant resource. It is probable that additional new resources can be identified by further exploration in this province; after all, large areas that contain metasomatic rocks have practically not been investigated for rutile in modern times.
- **Byproduct minerals.** In the case of rutile mining from eclogites, garnet would be a possible by-product mineral, while low-Ti eclogite which is not of rutile-ore quality, might be used for aggregate. Garnet from eclogites in the Førdefjord region is fine-grained, which is an disadvantage, while the garnet from eclogites elsewhere is often relatively coarse-grained. A variety of by-product minerals might be produced from the rutile deposits in the Bamble province, such as albite from the rutile-bearing albitites, and phlogopite and REE-bearing apatite from the Ødegården deposit.

2.3. Suggestions for further investigation

- The Vevring (Engebø) – Naustdal area needs to be further investigated. Firstly, the character of the Steinkorsen eclogite should be investigated at depth by core drilling, and a relatively detailed geological mapping should be done to map out and investigate more closely the various varieties of eclogites found in the area. Then, the geologic information obtained from the surface observations should be integrated with the gravity data into new and more detailed 3-d models of the occurrences of eclogite. This investigation will

have the advantage of dealing with a reasonably well-defined situation; and the chances for a successful continued exploration would be fairly good.

- The rutile-potential in the Dalsfjord region should be further investigated for new eclogite deposits by a combination of gravity profiles and geological follow-up investigations. The Dalsfjord region has the advantage compared to the Førdefjord region that the rutile is less fine-grained. A disadvantage, however, is that the known deposits looks less favourable in terms of deposit size for the high-grade ores.
- The rutile potential of the Holsnøy area of the Bergen region should be further investigated, based on a similar argument as for the Dalsfjord region.
- The rutile-locality information database and the corresponding ArcView maps need further refinements. More text, analytical information and illustrations should be incorporated in the database, making the database a more convenient tool in the continued rutile exploration in Norway.
- Information obtained by the DuPont-NGU project in 1995 of follow-up sampling and analyses of eclogites in the Dalsfjord region and a few other places, which will be open-file at the end of 2000, should be incorporated into the database as soon as that is permitted.
- Recognisance sampling should be done in some eclogite areas in West Norway which have not been investigated for rutile by NGU or DuPont, such as some of the eastern parts of the Nordfjord, Ålesund and Molde regions.
- A few scattered rutile occurrences outside the rutile provinces, from which very limited information is known, should be investigated.
- Rutile mineralogy and mineral chemistry need to be investigated, particularly the various variations of metamorphic transformation from ilmenite-bearing rocks to rutile-bearing rocks, and the formation of titanite from rutile during retrograde alteration of the different ore-types.
- The role of major hydrothermal systems in the formation of rutile-bearing rocks require further investigation. Such hydrothermal systems not only form rutile deposits, but do also provide a mechanism which leaches metals such as Fe, Cu and Cu from large volumes of source-rocks, to be precipitated at higher levels in the crust into various types of epigenetic hydrothermal ore deposits.

3. Confidentiality

Much of the compilations in the form of text, figures and tables that are presented in this report, is confidential, while the source-data for these compilations is open-file. Table 1 specifies the confidentiality situation for the various parts of the report.

Table 1: Confidentiality

Part of report	Confidential until 01.03.2002	Confidential until 01.03.2005	Open-file Information *
Text	Chapt. 6	Chapt. 1, 2, 3, 5 [#] , 7, 8, 13	Chapt. 4, 9, 10, 11, 12, 14
Figures:	Figs. 29-34	Figs. 4-28, 35-38	Figs. 1, 2, 3
Tables:	Table 4	Tables 1, 2 [#] , 3 [#] , 5, 6	
Appendix:		App. 4, 5	App. 1, 2, 3, 6, 7, 10, 11, 12

* These chapters are based on open-file information that continue to be open-file. However, information obtained by the RTIT/NGU-project that might be included, is confidential until 01.03.2005.

^{#o} The use of information about the Engebøffellet deposit is regulated by the agreement between DuPont/Conoco and NGU. In this case release of information is permitted by Jan Egeland in Conoco.

4. THE GEOLOGIC PROVINCES

4.1. Eclogites of W. Norway

Summary: The eclogite province of W. Norway is subdivided into 8 geographic regions (Fig. 3). The three southernmost of these regions, Holsnøy, Dalsfjord and Førdefjord, are surrounded by large areas without known eclogites, while the regions from Nordfjord and northwards form parts of a large eclogite terrain.

In general, eclogites in the northwestern parts of the gneiss region of W. Norway, i.e. the western parts of the Nordfjord, Ålesund and Molde regions, have been formed at the highest P,T-conditions, but significant variations occur due to major tectonic events after the eclogitization period at c. 400 Ma. The details of such inhomogenities in the regional P,T-pattern remain to be investigated.

Eclogite protoliths are Proterozoic and probably also Cambro-Silurian. Basaltic volcanic rocks and a variety of Proterozoic intrusions belonging to ultramafic-mafic, mafic and mafic-intermediate (gabbro-anorthositic) suites are the most important protoliths.

The rutile contents are generally 1-3%; 3-5% rutile and more occur within some eclogites in the Holsnøy, Dalsfjord and Førdefjord regions. Occurrences of high-Ti eclogites are less common, but not absent, in the northern regions. The northern regions are, however, much less investigated with respect to titanium in eclogites, and other Ti-rich occurrences are likely to exist.

The amount of titanium present as rutile is highly variable. Some eclogites in the Førdefjord, Dalsfjord and Nordfjord regions have 80-90% of the titanium in the rock as rutile; many eclogites in the Førdefjord and Dalsfjord regions are large bodies, while all the known eclogites in the Nordfjord region are relatively small. Most eclogites, at least in the northern regions, have a comparatively low rutile/TiO₂-ratio. The reason for this variation is unknown except in those cases where rutile has been altered to ilmenite ± titanite as a consequence of retrograde amphibolite or greenschist facies metamorphism.

Titanite occurs in very small amounts as rims surrounding rutile/ilmenite grains in major eclogite deposits such as Husebø, Saurdal, Engebøffellet and Vassbotn. It is frequently found in thin-sections of the most retrograded eclogites, i.e. mainly in eclogites from the eastern parts of the Kristiansund, Romsdal and Nordfjord regions. It seems to be less frequent in the western and southern terrains.

Eclogite protoliths: Most eclogites in W. Norway occur as lenses within gneisses and lack clear indications of the nature of their protoliths. Others are clearly eclogitized intrusions either with obvious intrusive relationships to the surrounding rocks, or with relict gabbroic textures. Large volumes of eclogite in the Førdefjord region might be of volcanic origin. These meta-volcanic rocks are intruded by eclogitized basic intrusions. A comparable situation occurs in the Averøy area (Kristiansund region) where basic host-rocks to stratabound sulfides (volcanogenic Cu-Zn deposits) were intruded by Ti-rich dykes before eclogitization.

Eclogitization and retrogression: It is generally accepted that the Basal Gneiss Region in W. Norway was metamorphosed under eclogite facies conditions around 400 Ma with the highest P,T-conditions in the northwest, i.e. the western parts of the Nordfjord, Ålesund and Molde regions (Krogh, 1977a,b; see also the discussion of P,T-relations in Griffin, 1987). The eclogitization of basic rocks is incomplete. Gabbros showing gradual transitions into eclogites occur in many places from Holsnøy in the south to the northernmost parts of the Kristiansund region. Gradational variations from gabbro to eclogite are described from Nordøyane SW of Molde (Mørk, 1985a and b; 1986), from the Surnadal area (Tørudbakken, 1981), from the Gjemnes, Halså districts, from the Gulen district (Korneliussen, 1989) and from the Gjøllanger-Flekke area in the Dalsfjord region where gabbroic to anorthositic rocks show gradual transitions to eclogite (Cuthbert, 1985). Eclogitization of basic rocks along shear zones is well documented at Holsnøy by Austrheim & Griffin (1985) and Austrheim (1987, 1990).

Large areas within the west Norwegian eclogite province do not show signs of eclogitization of basic rocks; this may be either because they never underwent eclogite facies metamorphic conditions or because extensive retrogression has obliterated the signs of eclogite. The probability is that the Basal Gneiss Region of W. Norway reached eclogite facies conditions 400 m.y. ago, and then underwent a period of major tectonic events that positioned geologic units in a complex pattern of nappes that have experienced different metamorphic and deformational histories.

The mineral reactions during the eclogitization process are complex. *In this context an important observation is that ilmenite from the mafic protolith reacts with feldspar and form garnet and rutile.* The titanium remaining when the iron from ilmenite enters into garnet, forms rutile. Another factor that will increase the proportion of Ti as free rutile in eclogite facies rocks is the very low solubility of Ti in chain silicates i.e. pyroxenes (and amphiboles) at high P. The Ti-content in basaltic and gabbroic pyroxenes (Ti-augites) protoliths, however, may be very high. Ti in the igneous pyroxenes is incorporated by the Ti-tschermak substitution: $(\text{Mg}^{2+})^{\text{VI}}(\text{2Si}^{4+})^{\text{IV}} \rightleftharpoons (\text{Ti}^{4+})^{\text{VI}}(\text{2Al}^{3+})^{\text{IV}}$. The Ti-tschermak molecule (component) is dominated by tetrahedral Al, and this results in a large unit cell which is very unfavorable for hosting Ti in the cell structure at high P. Therefore, Ti is released from pyroxenes during eclogitization of gabbroic rocks.

During retrogression the omphacitic clinopyroxene of the eclogite mineral paragenesis breaks down to symplectitic aggregates of plagioclase and diopside, +/- hornblende that may replace diopside. In this alteration rutile may break down to ilmenite, but normally it is unaffected. At more extensive retrogression garnet tends to break down to hornblende. At that stage rutile is altered to ilmenite and occasionally also to titanite. In the completely amphibolitized eclogites titanite+ilmenite are the characteristic Ti-bearing minerals. Such retrograde formation of ilmenite or ilmenite+titanite tends to occur along cracks or shear zones within eclogite bodies as well as along the margins of the bodies.

Titanite: Titanite has been found as narrow rims around grains of rutile/ilmenite in major rutile deposits such as Husebø, Vassbotn, Saurdal, and Engebøfjellet. The amount of titanite within these deposits is, however, minor relative rutile/ilmenite. Microscopy of thin-sections from many scattered eclogites within the eclogite province of W. Norway shows that titanite is a fairly common mineral, especially in the northern and eastern regions where retrogression is extensive. *Chloritization* may or may not lead to the formation of titanite. At the Saurdal eclogite (Sunnfjord region) chloritization is accompanied by a significant CaO-loss from 7-8% CaO in the eclogite to 1-2% CaO in the chlorite schist that is the end-product of this metamorphic and metasomatic process (based on X-MET analyses of old drill-cores). Apparently there is not enough CaO available in the chloritized rock to form titanite.

Size and form of eclogite bodies: Eclogites in W. Norway usually form bodies or lenses less than 200m long surrounded by gneisses. Large eclogites of more than 1 km in length occur mainly in the Dalsfjord and Førdefjord regions and in the Ulsteinvik, Eide and Averøy areas in the Ålesund, Molde and Kristiansund regions, respectively. Some scattered occurrences of big eclogites occur elsewhere.

At Holsnøy eclogites may occur along distinct fractures or shear zones in the form of cm- to dm-thick bands, as eclogite breccias with 1 to +10 m-large eclogite fragments within non-eclogitized granulites, or as completely eclogitized rocks over several hundred meters in length.

In the partly eclogitized gabbros in the Molde and Kristiansund regions eclogitization has occurred either at the margin or along shear zones within the gabbro bodies. Such eclogite zones are from a few decimeters to a few hundred meters in thickness.

The rutile contents in W.Norwegian eclogites are generally 1-3% but 3-5% rutile is fairly common within eclogites in the Førdefjord, Dalsfjord and Holsnøy regions. The eclogites richest in rutile, and also of significant size, are those at Engebøfjellet, Naustdal

village and Fureviknipa in the Førdefjord region, at Saurdal, Ramsgrønova and Orkheia in the Dalsfjord region, and at Husebø in the Holsnøy region. Some eclogite localities in the Kristiansund and Romsdal regions have TiO₂-contents as high as 3-6%, locally.

Unfortunately, the proportion of ilmenite to rutile is high in these northern regions.

Rutile occurs in aggregates or as disseminated individual grains. The individual rutile grains are usually in the range 0.1 - 1.0 mm. In general, rutile from the southernmost regions, i.e. Holsnøy and Dalsfjord, is coarser-grained than further north, but there are large local variations.

TiO₂ (rutile) vs. TiO₂ (total): Electron microprobe analyses of silicate minerals from eclogites in the Førdefjord and Holsnøy regions have shown that garnet and clinopyroxene contain approximately 0.1% TiO₂, amphibole 0.2-0.4% TiO₂ and micas 0.4-0.8% TiO₂ (Korneliussen & Foslie, 1985). In most eclogites, titanium in silicates can be neglected for practical purposes at least at the reconnaissance stage of investigation.

An analytical procedure that determines the amount of rutile as the difference between total TiO₂ (XRF-analysis) and HCl-dissolved TiO₂ (ICP-analysis) has been established at NGU. The TiO₂ analysed by ICP gives the titanium in ilmenite. Titanium in silicates, including titanite, is assumed to be close to zero and therefore is negligible in these calculations. 500-600 samples have been analysed at NGU since 1990 by this method and have given reliable results.

According to such rutile analyses, approx. 90% of the titanium in the Engebøfjellet, Drøsdal and Orkheia eclogites is in rutile. In other eclogites where several analyses are available TiO₂ (rutile) vs. TiO₂ (total) varies wildly, though 60-80% of the titanium as rutile is most common.

4.2. The Bergen region

Ti-rich rocks associated with a large Proterozoic anorthosite complex (c. 1000 m.y.) in the Bergen region of W. Norway (Fig. 5) have, in the northern parts of Holsnøy (Fig. 6), been metamorphosed to eclogites along Caledonian (c. 400 Ma) shear zones. Anorthositic rocks are dominant in the region. They vary from pure anorthosite through gabbroic anorthosite to leucogabbro. These rocks are normally very low in titanium, but may occasionally contain minor Ti-enriched layers or segregations and Ti-enriched dykes of garnet-pyroxenitic composition. Dykes and larger bodies of jotunite rocks frequently intrude the anorthosite. The jotunite rocks contain large amounts of low-grade ilmenite mineralization/dissemination. Other rocks in the area are gabbros, spinel-lherzolites, mangerites, garnet-pyroxenites and banded granulites. These rocks have crystallized at approximately 1000 Ma in the following order: anorthosite, gabbro, Ti-rich garnet-pyroxenite, jotunite, Fe-Ti-P-rich garnet-pyroxenite, and mangerite (Austrheim, 1990). They were metamorphosed under granulite facies conditions during or shortly after the time of crystallization and experienced high-pressure Caledonian metamorphism (c. 400 Ma) with eclogitization in shear zones (see Austrheim & Griffin, 1985; Austrheim, 1987 and 1990; Austrheim & Mørk, 1988; Jamtveit et al., 1990).

One fairly large deposit occurs at Husebø within eclogitized jotunite, covering an area of about 100.000 m². The average TiO₂-content based on surface samples is 3.6% TiO₂, but higher contents do occur within parts of the deposit. Approximately 60% of the titanium is in the form of rutile and 40% in ilmenite. Other mineralizations at Holsnøy may have higher rutile-contents than Husebø,

but are too small to have economic interest. Holsnøy rutile mineralizations are the most coarse-grained of the rutile/eclogite deposits known in Norway, but tend to be intergrown with ilmenite. Ilmenite from Husebø and other deposits at Holsnøy have a low MgO-content (< 1% MgO). The region is close to Bergen and is fairly densely populated. The environmental conflict in case of mining is expected to be large.

The main focus on NGUs investigations in this area (1989-90) was the Husebø deposit, while other eclogites at Holsnøy and in neighbouring areas were only roughly investigated. Consequently, significant deposits, particularly in areas with much overburden, might not have been found. The rutile ore potential of this area has not been sufficiently investigated. In case of continued investigations, a combination of gravity profiles and geological follow-up should be carried out.

4.3. The Dalsfjord region

This region contains a variety of gneisses, and basic (incl. anorthosites), ultrabasic and Fe-Ti oxide-rich rocks; the basic rocks are frequently eclogitized. Massive bands and impregnations of magnetite-ilmenite occur within gabbroic, partly eclogitized rocks. Some of these were mined for magnetite at the beginning of this century. The largest of these deposits is at Saurdal where up to 0.5 m thick bands of massive magnetite-ilmenite occur along an E-W trending 800 m-long zone along the southern margin of an eclogitized gabbro. Investigations in 1993-94 by the DuPont/NGU project were concentrated on the Dalsfjord region, mainly focusing on rutile-bearing eclogites in the Gjørlanger-Saurdal area and westwards towards Drøsdal/Orkheia/Seljevoll.

Rutile-bearing eclogites in the Dalsfjord region were investigated by NGU in 1978-79 (Korneliussen 1980, 1981). The central part of this region, at Hellevik-Gjørlanger-Flekke, was investigated by S.Cuthbert in a doctoral thesis (1985). This region contains a variety of gneisses, and basic, ultrabasic and Fe-Ti oxide-rich rocks; the basic rocks are frequently eclogitized. Many eclogites had demonstrably low-pressure igneous protoliths and/or show intrusive relationships with the gneisses, indicating a crustal, eclogite-facies metamorphism of all lithologies. Relics of early granulite-facies assemblages occur in most lithologies (Cuthbert 1985). Associated eclogites have been metasomatically altered but retain some tholeiitic characteristics. The Flekke unit rocks have affinities with some layered basic intrusions typical of mid-Proterozoic anorthosite suites. Mineral chemistry and parageneses of a variety of lithologies indicate an early (presumably Proterozoic) granulite-facies event at 7-13 kb, and 750-1000°C, followed by metamorphism to high-pressure eclogite-facies conditions at 597±30°C, and decompression during exhumation to below 6 kb. Such a P-T path is incorporated into a continental collision model for the Scandinavian Caledonides involving transient "subduction" of the Basal Gneiss Complex in a Himalayan-style collision zone (Cuthbert, 1985).

Ane Engvik (Univ. Oslo) is about to finalise a Ph.D. thesis on the gabbro – eclogite relationships in the Gjørlanger area.

Figs. 8-10 gives a geological overview of the Dalsfjord region, including various photographs with accompanying text to illustrate some of the characteristics of this area.

The DuPont-NGU project paid significant attention to this area during 1992-94. Some of the results from the investigations that were done are shown in the form of various graphs within Fig. 8. In general, rutile from eclogites in the Dalsfjord region is relatively coarse-grained, as shown in the grain distribution graphs in Fig. 9. However, good indications of *large volumes* of rutile/eclogite ores with 3-5 % rutile was not found, and in the autumn of 1995 the focus was

taken away from the Dalsfjord region in favour of the Engebøfjellet eclogite deposit (Chapt. 4) on the northern side of Førdefjord.

However, the Dalsfjord eclogite province might very well contain significant rutile/eclogite deposits yet to be identified. Based on the experiences with using gravimetry in rutile/eclogite exploration in the Førdefjord region which resulted in the discovery of the Steinkorsen occurrence, continued investigations in the Dalsfjord region should be based on a combination of gravity profiles and geological follow-up investigations.

4.4. The Førdefjord region

General geology

(based on Korneliussen et al. 1998)

The Førdefjord area is a part of the Proterozoic Western Gneiss Region of Norway. This area and adjacent areas to the south and north, are folded into regional east-west trending folds, interpreted to be the result of late-Palaeozoic N-S compression. Two major units are present in the area: the Hegreneset complex and the Helle complex.

The Hegreneset complex (Figs. 10 and 11) consists of a variety of mafic, mainly eclogitic rocks, and crosscutting, homogeneous grey to grey-green tonalitic, dioritic and granodioritic intrusives. The mafic and felsic rocks are in many places intimately mingled, in several places with a broad intrusive contact zone where the grey intrusives have abundant basic xenoliths. The Hegreneset complex crops out continuously on the southern side of Førdefjord from Hegreneset in the west to near Førde in the east. It seems to be situated in a major late-Caledonian east-west elongated dome structure. On the northern side of the Førdefjord, it crops out in the Engebø area, and from Engebø it can be followed discontinuously eastwards, surrounded by rocks of the Helle complex.

At Mt. Fureviknipa (Fig. 11) on the southern side of the fjord, banded eclogite represents eclogitized layered gabbro. Westwards from Fureviknipa, anorthosite and leucogabbro constitute part of the same basic complex; the anorthosite contains lenses of retrograded eclogites. The large basic complex south of Førdefjord, including Mt. Fureviknipa, therefore consists mostly of plutonic layered cumulate rocks. Southwest of Mt. Fureviknipa, a fine-grained, banded to laminated, basic rock of either intrusive or extrusive origin occurs. This rock shows extensive mesoscopic, ductile, disharmonic folding under eclogite facies conditions; and resembles the Engebøfjellet eclogite. In some places, such as the country-rocks to the Engebøfjell eclogite body, mafic and felsic rocks occur in a characteristic deformed cm-dm scale banded succession as well as in larger units.

The Helle complex consists mainly of granitic to granodioritic gneisses, in many places migmatitic and/or banded. The granitic gneisses are red to grey. A number of younger red granites altered to gneiss, and minor basic intrusives are also included in the complex. Due to the complex, polyphase, and generally strong deformation in the area, rocks with varied structures and textures occur.

Rutile-bearing eclogites

Eclogites in the Førdefjord region frequently occur as several kilometer-long folded and boudinaged layers with thicknesses in the range of 10 meter to a few hundred meters. Some of the larger boudins are fairly massive eclogite bodies covering areas of more than 100,000 m² (e.g. Engebøfjellet). The TiO₂-content is generally 1-3%, but contents of 4-5% TiO₂ or more are not uncommon. The high Ti-contents are often, but not always, associated with fairly massive parts of the eclogites.

Rutile in eclogites in the Førdefjord region was first mentioned by Eskola (1921) from the Naustdal village eclogite, and then by Binns (1967) who presents a TiO₂-analysis of 6.44%. H.P. Geis from Elkem A/S recognised an economic potential related to the Førdefjord rutile-bearing eclogites in the middle 1970s. In collaboration with Elkem A/S, NGU did reconnaissance mapping of eclogites in the Førdefjord (and Dalsfjord) region in 1978-80 (See Korneliussen, 1980 and 1981; Foslie, 1980, Korneliussen & Foslie 1985). These investigations resulted in the discovery of several large eclogite bodies with rutile contents of 1-3%. Locally the rutile content reaches 3-4% or more.

In 1979 Frank Barkve and his companion Tore Birkeland recognized the Engebøfjellet eclogite body as potentially suitable material for breakwater purposes. They did not succeed in putting the deposit into production and Birkeland withdrew from the project after a few years. Barkve's Engebø-project has now been taken over by the company Fjord Blokk.

Rutile-investigations were continued by Norsk Hydro in 1984-85, including beneficiation tests on the Engebøfjellet eclogite (by Warren Spring Lab., England) and Fureviknipa (by prof. K. Sandvik, Technical Univ. of Norway, Trondheim), without success. NGU did new sampling of the Engebøfjellet and Fureviknipa eclogites in 1990 in order to obtain additional information about rutile-contents and rutile/ilmenite-proportions (Korneliussen & Furuhaug, 1991).

Continued investigations in the Førdefjord area were then carried out by DuPont/Stokke/NGU in 1992 to obtain additional information on TiO₂ contents in a number of previously known eclogites and to discover new rutile-bearing eclogites. In 1993 an attempt was made to find new eclogites eastwards from Naustdal. Several localities of low-TiO₂ eclogites similar to the so-called "volcanic eclogites" near Førdefjord were found more-or-less directly eastwards from Naustdal. Ti-rich eclogite varieties frequently occur as thin bands and lenses within the low-TiO₂ eclogite. The situation is comparable to the areas between Naustdal and Vevring/Engebø. This type of eclogite continues eastwards from Naustdal at least as far as Kleppestølen 15 km E of Naustdal, and probably much further.

In a river at Svorstølen (near Fimlandsgrend) approx. 30 km NE of Naustdal an anomalous number of Ti-rich eclogites that resemble the Naustdal and Engebøfjellet eclogites in grain-size and TiO₂ content were identified. These boulders indicate, even though their source was not found, that eclogite-bearing terrains of the Førdefjord region can be extended far eastwards and northeastwards from Naustdal. So far this large area has been only superficially investigated for rutile-bearing eclogites.

Based on the present knowledge, the largest rutile ore potential in Norway is on the northern side of the Førdefjord between Engebøfjellet (Chapter 4) in the west and Naustdal in the east, including the Steinkorsen area (Chapter 5) in between.

4.5. The Nordfjord region

Known eclogite localities in the Nordfjord region are shown in Fig. 12. In general, these eclogites are small bodies that are believed to represent eclogitized basic dykes. A characteristic feature of this region is an abundance of anorthosites, commonly forming concordant layers tens to hundreds of meters thick and many kilometers long. A regional association of ultramafic rocks, anorthosites and mangerites raises the possibility that these rocks could be part of a disrupted layered complex (Mørk and Krogh, 1987). Since Ti-rich rocks commonly are associated with anorthosites elsewhere, for example at Holsnøy, the anorthosites of Nordfjord might also be spatially associated with Ti-rich rocks that include eclogites.

Only three samples of Nordfjord eclogites have been analysed for rutile. The TiO₂-content is low. A dominant part of the titanium in the rock resides in rutile (Fig. 12). Microscopy shows that a significant portion of the rutile/imenite minerals occur as distinct grains.

However, no indications of eclogites of economic interest have been found in the Nordfjord region.

4.6. The Ålesund region

One large eclogite in the Ulsteinvik area (Fig. 13) forms a sheet of approximately 25 km², but is only about 300 m thick (Grønlie et al., 1972). The chemical composition is transitional alkali olivine basalt and olivine tholeiite (Mysen & Heier, 1972). The metamorphic peak has been estimated at ca 800°C, 18 kb by Griffin et al. (1985). The Ulsteinvik and other eclogites in the area tend to be fairly retrograded and low in TiO₂. An exception is an eclogite at Aurvåg that shows X-MET TiO₂-values varying between 2-3% and 15% (mainly ilmenite) over a 2-3m thick zone in a 200-300 m long eclogite body that contains approx. 2% TiO₂ in average.

In the Volda district south-east of Ulsteinvik, a number of relatively small eclogites are known, and some of these are believed to be eclogitized remnants of Proterozoic layered intrusions (cf. Erambert, 1985). Decimeter-thick layers within mafic and ultramafic eclogitized layered rocks have occasionally a few percent rutile (samples given to A. Korneliussen by M. Erambert in 1990).

At Vassbotn a few kilometers north of the town of Volda a fairly large and extremely garnet-rich eclogite outcrops on a mountain slope. The TiO₂-content is 2-3%, mainly in the form of rutile. The company Novemco has recently investigated this deposit for garnet. The mineralogical features of the Vassbotn eclogite are comparable to those of Ti-rich layers in layered, eclogitized mafic intrusions elsewhere in the Volda district (Muriel Erambert, pers. comm. 1994).

Good indications of eclogites of economic interest for rutile has not been found in the Ålesund region.

4.7. The Molde region

A large number of eclogites occur north and northeast of Molde in the Fræna and Eide districts (Fig. 14). Reksten (1985) describes eclogites in the Eide area. Most of these eclogites are small with TiO_2 -contents of 1-3% (based on a few analysed localities). At Eide a large volume of garnet-amphibolite/eclogite is associated with indisputable metasedimentary rocks including carbonates. The protoliths for these eclogites are presumably of volcanic origin; they continue northeastwards on the island Averøy (Kristiansund region) where the same basic rock units are the host-rocks for stratabound massive sulfide deposits.

Analysed eclogites have 1-2% TiO_2 of which less than 50% occurs in rutile (Fig. 14). Certainly the eclogite protoliths have not been of Ti-rich types, and the eclogite metamorphism has partitioned only 40-60% of the titanium into rutile. The rutile/ilmenite is not intergrown with garnet and might, for that reason, be fairly easy to concentrate.

So far the region does not look interesting for rutile although the possibility for major rutile/eclogite deposits cannot be excluded.

4.8. The Kristiansund region

At Averøy (Figs. 14 & 15) large volumes of low- TiO_2 (1-2%) basic rocks of volcanic origin are metamorphosed into garnet-amphibolites and eclogites. At Helset (Fig. 14) the dominant low- TiO_2 eclogite is intruded by dm-thick dykes (eclogitized) with 3-9% TiO_2 . Thin-sections show that ilmenite is more abundant than rutile. Further northeast on the islands Frei and Tustna (Fig. 15) the eclogites tend to occur as fairly small, boudinaged, low- TiO_2 bodies within gneisses.

In the Gjemnes and Halså districts further east, the eclogitization has been less complete; a number of gabbroic intrusions show gradual transition into eclogite. TiO_2 -contents are generally 1-2%, though contents of 3-4% occur occasionally. The TiO_2 -content in eclogites in the Kristiansund region varies between 1% and 4% TiO_2 , with a highly variably rutile/ilmenite ratio.

The eastern parts of the Kristiansund region that contain Fe-Ti-rich amphibolites and metagabbros should be investigated in order to find eclogitized portions of these rocks. Eclogites in these areas have experienced significant retrogression in general, but there are probably large local variations.

Fairly high ilmenite/rutile ratios and the fact that titanite is a common mineral cast doubt on the potential of these areas even if high-Ti eclogites do occur.

4.9. The Romsdal region

Eclogites in the Romsdal region (Fig. 16) are rather scarce, presumably due to lesser amounts of favorable basic protoliths. Eclogites in the Lesja district tend to be fairly titanium-rich (3-4% TiO_2). Many of the eclogite bodies are small, but some may be large (covering areas of more than 100,000 m^2). However, the rutile portion of the titanium is low due to significant retrogression that causes rutile alteration to ilmenite and also to titanite.

4.10. Other eclogite localities

In the Rausand district (Fig. 14) large volumes of vanadium-bearing magnetite-ilmenite ore are associated with amphibolites surrounded by a variety of gneisses (see Sanetra, 1985). A possibility that remains to be tested is that such magnetite-ilmenite ores have been the protoliths for Fe-Ti rich eclogites elsewhere in the region, perhaps resulting in large volumes of rutile-rich eclogites.

At Dalsfjell in the Gulen area between the Holsnøy and Dalsfjord regions a large gabbro has been incompletely eclogitized. The TiO₂-contents are in the range 1-4% with 50-80% of the titanium as rutile (Korneliussen, 1989). The largest eclogites in this area occur at Slengesol, Nordal and Kjelby (also called Kjellbju) where the eclogitized areas are up to 3-400 m long and 100 m wide.

Westwards from Dalsfjord a number of eclogite localities are known on the island of Byrknesøy. The main eclogite body at Byrknesøy is an approx. 1 km long eclogite body called Vetén, which was sampled by the DuPont-NGU project in 1995 (additional information from this deposit is confidential out 2000).

4.11. Rutile-bearing rocks in the Bamble region

The Bamble-region (Fig. 17; also “The Bamble-Arendal region” or “The Bamble Sector”) of the Baltic Shield is a geologic province that is anomalously rich in mineral deposits of various types, and one where mining has traditionally been important. The region's anomalous character with respect to mineral deposits may reflect unique, but poorly understood, circumstances in its geologic evolution.

The oldest rocks known in the region are supracrustals which are intruded by several generations of basic and acidic intrusions. De Haas (1992) reports Sm-Nd ages of 1670 and 1640 Ma for two gabbroic intrusions in the Arendal area. This early period, *The Gotian Orogen*, in the region's geologic evolution lasted for approximately 250 m. y. (1500-1750 Ma; see references in de Haas, 1992 and Starmer, 1991). The maximum metamorphism in this period was at 700-800°C and 6-8 kb (granulite facies; see Touret, 1971 and Lamb et al., 1986).

The region then experienced a fairly quiet geologic period until *The Sveconorwegian Orogen* (990-1250 Ma), which was characterized by significant basic magmatic activity followed by a period of granulite facies metamorphism. In certain parts of the region, for example at Ødegården, significant hydrothermal activity caused extensive metasomatic alteration of the basic rocks. This geologic period was terminated by the intrusion of large, post-tectonic granites (990 Ma; Kullerud and Machado, 1991). According to Starmer (1991) the basic magmatism was associated with an anorogenic early phase in the Sveconorwegian orogeny, and was associated with extensional tectonics followed by an orogenic phase with nappe tectonics. De Haas (1992) also supports an extensional model; according to de Haas the mantle from which the Sveconorwegian gabbros were derived, domed up under a relatively thin crust. This mantle doming led to high temperature/-pressure-gradients and granulite facies metamorphism in the overlying crust.

Smalley and Field (1991) have another opinion: based on trace element characteristics for the Sveconorwegian gabbros they claim that the gabbros formed at an active continental margin.

Regardless of which of these two models are preferred, the significant hydrothermal activity that was active in the region altered the basic intrusions that are believed to have formed during the first part of the orogen, and must, therefore, be younger than the intrusions. The hydrothermal activity is most likely related to the last part of the orogenic activity.

Post-Sveconorwegian magmatism in the form of scattered carbonatitic dykes and alkaline basic dykes is associated with the Fen carbonatite complex (600 Ma.) and the Permian magmatism in the Oslo Graben (270 Ma).

Of the rutile-bearing rock-types, coordierite-bearing metasediments and scapolitized and albitized gabbros occur in large volumes and may have an economic potential with respect to rutile. No significant investigation has been done on the rutile-bearing metasediments, while NGU (1990-91) investigated the scapolitized gabbros at Ødegård (Fig. 19) for rutile, including the core-drilled of two holes. The Ødegården deposit covers an area of more than 100,000 m² with the rutile contents varying between 2% and 4%. The deposit is heavily covered by vegetation. See Korneliussen and Furuhaug (1993) and Sandøy (1995) for additional information.

The two drill-cores from the Ødegård deposit have been studied in order to investigate the details of the gabbro to scapolitized gabbro transition. Major- and trace element analyses from this study are given in Appendix 2 while Table 1 gives a compilation of average analytical values for the various rock varieties that were distinguished in these cores. Based on these data the chemical variations with increasing metasomatism can be demonstrated. The variations in Fe₂O₃, TiO₂ and rutile contents with increasing metasomatism (scapolitisation) are shown in Fig. 20 (1). During the transformation of gabbro to the scapolite-hornblende rock (ødegårdite), the metasomatic fluids leaches a series of elements from the gabbro, to be carried away by the hydrothermal system. The major silicate minerals in the remaining rock is scapolite (after plagioclase) and a hornblende with low iron content (after mafic silicates in the original gabbro/amphibolite). The rutile is formed from the titanium remaining when iron from ilmenite was carried away by the fluids.

The drawing in Fig. 20 (2) is a generalized cross-section of the Earth's crust illustrating the formation of rutile-bearing rocks at a deep level by metasomatic processes leaching elements such as Fe, Cu and Cu, leaving titanium as rutile. The leached elements are transported to higher levels in the crust, presumably along major shear-zones, to be concentrated into various types of hydrothermal ore deposits due to changes in the physical and chemical environment.

The bar-graphs (3), (4) and (5) in Fig. 20 illustrates the related variations in major- and trace elements in the main rock-types metagabbro, scapolitized gabbro (ødegårdite) and the phlogopite-enstatite-apatite rock. In the scapolitization process elements such as Fe, Mn, Zn, Cu, Co, Zr, Sr, Ba and Eu are significantly depleted, while Mg, Na, K, V, Cr, Ni, U and Rb are enriched. The phlogopite-enstatite-apatite veins or dykes that intruded the scapolitized gabbroic rock along numerous fracture sones, are particularly enriched in Mg, K, P, V, Ni, As, Y, Th, Rb, La, Ce, Nd, Sm, Tb, Yb and Lu.

Table 1: Compilation of major and trace element analyses of the three main rock-types metagabbro, various variations of scapolitized metagabbro (ødegårdite) and phlogopite-enstatite-apatite veins/dykes at the Ødegård rutile deposit. Analyses by XRF and INA (marked *).

	Metagabbro				Scapolitized metagabbro (ødegårdite)						Apatite-bearing phlogopite-enstatite veins			
	MG1	MG2	MG3	Avg.	SMG1a	SMG1b	SMG1c	SMG1d	SMG3	Avg.	PEV1	PEV2	PEV3	Avg.
# of analyses	7	5	8		35	12	9	7	19		5	4	6	
% SiO ₂	45.48	41.83	51.95	46.42	50.06	49.85	49.11	47.41	56.28	50.54	44.86	42.89	35.80	41.18
% Al ₂ O ₃	14.25	11.19	13.74	13.06	16.25	16.35	16.20	15.91	14.24	15.79	11.69	12.84	10.30	11.61
% Fe ₂ O ₃	13.38	21.32	15.50	16.73	4.76	4.02	2.34	2.89	7.58	4.32	5.15	4.76	4.02	4.64
% TiO ₂	2.82	4.31	2.21	3.11	3.12	3.05	2.95	2.82	2.02	2.79	2.51	2.62	2.68	2.60
% MgO	6.59	4.13	2.29	4.34	6.90	8.20	11.65	13.93	3.51	8.84	21.13	19.68	16.73	19.18
% MnO	0.09	0.20	0.16	0.15	0.03	0.02	0.01	0.01	0.03	0.02	0.01	0.01	0.01	0.01
% CaO	8.48	8.56	7.10	8.05	8.18	6.53	4.28	3.60	7.37	5.99	3.52	4.45	11.73	6.56
% Na ₂ O ₃	5.22	2.78	4.18	4.06	6.49	6.23	5.64	4.69	5.75	5.76	1.92	2.08	1.64	1.88
% K ₂ O	0.66	1.10	1.08	0.95	0.53	1.32	2.42	3.54	0.43	1.65	3.95	4.41	3.44	3.93
% P ₂ O ₅	0.38	2.20	0.82	1.13	0.45	0.50	0.69	0.67	0.67	0.60	0.51	1.24	6.65	2.80
% LOI	0.58	0.71	0.15	0.48	0.87	1.41	2.05	1.89	1.22	1.49	2.12	2.04	1.98	2.05
% Sum	97.92	98.34	99.18	98.48	97.63	97.49	97.33	97.38	99.11	97.79	97.38	97.01	94.97	96.46
% Rutile	0.42	0.28	0.02	0.24	2.11	2.26	1.94	1.59	0.25	1.63	0.69	0.86	1.15	0.90
ppm Y	46	92	82	73	93	72	58	79	93	79	257	279	695	410
ppm Nb	7	10	15	10	7	8	8	9	15	9	7	8	17	11
ppm Zr	159	309	646	371	155	152	120	124	589	228	80	110	63	84
ppm U *	0.4	1.0	1.6	1	1.4	1.5	1.0	1.2	2.7	2	0.2	0.7	1.3	1
ppm Th *	1.1	2.4	3.9	2	1.5	0.6	0.4	0.5	5.3	2	6.0	11.9	8.0	9
ppm Hf *	4	7	13	8	5	5	4	5	14	7	3	4	3	3
ppm Ta *	0.8	0.9	1.3	1	0.8	0.6	0.7	1.1	1.6	1	0.2	0.5	2.5	1
ppm Rb	11	41	19	24	12	48	96	120	10	57	181	201	143	175
ppm Sr	175	188	251	205	106	88	82	66	193	107	6	14	44	21
ppm Ba	131	351	525	336	65	161	84	79	111	100	135	134	103	124
ppm Zn	39	81	54	58	19	25	16	14	15	18	20	18	15	17
ppm Cu	30	15	11	18	10	11	8	5	9	8	10	5	5	7
ppm Co	40	39	23	34	17	16	12	13	22	16	28	24	22	24
ppm Sc	36	45	47	43	41	40	36	38	46	40	36	44	32	37
ppm V	265	124	13	134	538	590	921	1217	109	675	2616	2914	2338	2623
ppm Cr	164	5	5	58	101	115	142	167	5	106	71	86	84	81
ppm Ni	103	5	5	38	125	147	131	160	19	116	285	330	286	300
ppm As *	16	20	14	17	16	16	15	16	18	16	17	15	65	32
ppm La *	16	45	48	37	18	15	16	20	94	33	14	26	145	62
ppm Ce *	58	116	116	97	64	61	67	76	170	88	48	82	512	214
ppm Nd	35	118	59	70	71	57	53	69	73	65	60	88	339	162
ppm Sm *	9.1	21.9	19.3	17	17.2	13.8	10.7	15.5	23.8	16	22.1	31.4	118.2	57
ppm Eu *	3	6	6	5	4	2	0	1	6	3	2	3	13	6
ppm Tb *	1.5	2.9	2.6	2	3.2	2.4	1.6	2.6	4.6	3	6.1	7.1	20.5	11
ppm Yb *	4	10	12	9	13	9	3	7	14	9	36	39	56	44
ppm Lu *	1.0	1.4	1.8	1	2.0	1.4	0.7	1.1	2.1	1	5.0	5.5	9.1	7

4.12. The Rogaland anorthosite province

The Rogaland anorthosite province (Fig. 21) is characterised by massif-type anorthosites and a large layered jotunitic intrusion (the Bjerkreim-Sokndal intrusion). It occurs in the Proterozoic Sveconorwegian Province, correlated with the Grenville Province in North America, where voluminous anorthosite massifs together with several of the largest ilmenite deposits in the World occur. In Rogaland, two major parental magmas are invoked to explain the whole anorthosite suite of rocks (Duchesne et al. 1987). These are a high-alumina basaltic magma that has given rise to the massive anorthosites, and a jotunitic magma that has differentiated into the Bjerkreim-Sokndal layered series of anorthosite/leuconorite – norite – gabbronorite – mangerite cumulates topped by quartz mangerites and charnockites (Wilson et al. 1996; Duchesne and Wilmart 1997). Ti-Fe oxide deposits are widespread in the province, and are primarily found as ilmenite rich, cumulate noritic rocks, or as a variety of ilmenite – magnetite rich dykes (Duchesne 1999). The major plutonism took place between 932 and 920 Ma (Schärer et al. 1996) 50-60 Ma after the last major regional deformation. The anorthosites have thus escaped tectonic reworking, in sharp contrast to most North American occurrences. Thus they are in their pristine state, providing an unique opportunity to study primary relations between anorthosites and ilmenite deposits, and more globally to address the geodynamics of anorthosite magmatism.

There is a long tradition for ilmenite mining in the Rogaland anorthosite province, starting in 1785 in the Egersund area where ilmenite ore was mined as iron ore. After pioneering research on utilising the Ti contents of the ilmenite, an industrial method of producing a white TiO₂ pigment today known as the sulphate process, was developed (Jonsson 1982), and the company Titania A/S started a titanium mining operation at the Storgangen deposit in 1917. In 1961 the production continued at the nearby Tellnes deposit. The present mining at Tellnes has an annual production of 500,000 – 600,000 t. ilmenite concentrate containing 44.7% TiO₂.

The Tellnes ilmenite norite orebody has a sickle-shaped outcrop (2700 m long and more than 400m wide in its central part) and is intruded into the Åna-Sira anorthosite. It is spatially associated with a series of slightly older jotunitic to mangeritic dykes. U-Pb ages on zircon and baddeleyite from the ilmenite ore-body are 920 Ma, thus distinctly younger than the surrounding anorthosite (932 Ma) and the jotunitic dyke (931 Ma) (Schärer et al 1996). It is suggested that the deposit was injected as a crystal mush lubricated by interstitial Fe-Ti-rich silicate liquid (Wilmart et al. 1989).

Large volumes of anorthosite, particularly in the coastal parts of the province, consists of white, altered anorthosites. At Hellevik and Rekevik such anorthosites are being mined for aggregate. The white anorthosites have formed by the break-down of plagioclase to fine-grained aggregates of albite, quartz and white mica along fracture zones in various scales. In some areas several km² of white anorthosites have formed by this mechanism.

NGU is presently carrying out a project for the Rogaland county on mapping and characterisation of the white anorthosites. Because several competing companies have an interest in this rock for aggregate, it has been decided to keep the information obtained so far within this project confidential until the release of a report in the spring 2000.

The white anorthosites in the coastal areas have a low Ti-content ($< 1\%$ TiO_2), in contrast to some anorthosite varieties further inland that might contain distinct dissemination of ilmenite. In some cases ilmenite has been replaced by rutile + titanite, as illustrated in Figs. 22 & 23. Rutile mineralisations that in size and quality might have a chance of becoming of economic interest have not been identified.

However, the mapping and understanding of the white anorthosites have just started, and there are still large areas that have not been investigated. The possibility of significant rutile deposits associated with hydrothermal alteration of anorthosites cannot be ruled out at present.

5. THE ENGEBØFJELLET DEPOSIT

Based on Korneliussen et al. (1998).

The Engebø - Vevring area located on the northern side of Førdefjord, is characterised by a series of mafic rocks (eclogitic and amphibolitic) intermixed with grey gneisses. The eclogitic rocks are mainly of a garnet-poor, amphibole-rich type, with gradational transitions into garnet-amphibolites and amphibolites. Generally, the eclogite to amphibolite transition is an effect of retrogression. The grey gneisses which are intimately associated with the mafic rocks, are of two types: cm-dm thick leucocratic bands (quartz + feldspar + white-mica) alternating with mafic bands of garnet amphibolites and eclogites, and granodioritic to tonalitic gneisses within units several meters to several tens of meters thick. The Engebøfjellet eclogite and the surrounding undifferentiated mafic and felsic rocks belong to the Hegreneset complex, see the Førdefjord geologic map (Fig. 24). Larger units of granitoid gneisses belong to the Helle complex.

The Engebøfjell eclogite forms a 2.5 km long E-W-trending lens (see Fig 24) with a distinctly massive character compared to the surrounding rocks. It is believed to represent a Proterozoic gabbroic intrusion that experienced crystal fractionation processes leading to the enrichment of Fe and Ti, and transformed into eclogite during Caledonian high-pressure metamorphism at approx. 400 Ma. In this process ilmenite in the protolith has been replaced by rutile, and the Ti-enriched parts of the body is now rutile ore. The TiO_2 -content of the ore is illustrated in the Fe_2O_3 - TiO_2 plots (Figs. 25 & 26). Relict magmatic zircons from the leuco-eclogite variety at Engebøfjell has recently been dated at 1500 Ma (pers. comm. from Thomas Krogh, Royal Ontario Museum, Canada).

In the Engebøfjell geologic map, the body is subdivided into two major eclogite types based on their varying iron and titanium contents: (1) The *ferro eclogite* is Fe_2O_3 -, TiO_2 - and garnet-rich; $>14\%$ Fe_2O_3 , $>3\%$ TiO_2 and $>25\%$ garnet, respectively. In general, it has a more massive character than the other eclogite varieties found at Engebøfjellet, although in parts it is significantly banded and folded. This eclogite is the rutile ore-type eclogite, the major volume of which is found in the central and western parts of the deposit. This eclogite occasionally shows fairly sharp contacts to the leuco eclogite (see below), but usually the contacts are gradational over several decimetres to several meters via a «transitional» eclogite variety.

(2) The *leuco- and transitional eclogite* is TiO_2 - and Fe_2O_3 -poor ($<14\%$ Fe_2O_3 and $<3\%$ TiO_2), locally with preserved gabbroic protolith textures. Metagabbroic relict textures are

more abundant in the western parts of the deposit, whereas this rock-type not has been mapped in the eastern part of Engebøfjellet.

Geochemistry: The geochemistry of the Engebøfjell eclogite is a reflection of its complex geologic evolution, and mirrors both primary magmatic chemical variation in the Proterozoic gabbroic protolith and probably also the influence of Caledonian metamorphism.

Based on a large number of Fe_2O_3 and TiO_2 analyses of cores by a portable XRF spectrometer (Fig. 25) and analyses of surface sample, some general features can be observed. Firstly, the Fe_2O_3 - TiO_2 chemical variation is continuous from leuco eclogite and through transitional eclogite into ferro eclogite. Secondly, the ferro eclogite ($>14\%$ Fe_2O_3 and $>3\%$ TiO_2 , approx.) can be split into two groups, a «normal ferro eclogite» that is a direct-line

Table 2: Exploration history, Engebøfjellet eclogite deposit.

Year	Information
1975	The Elkem geologist Hans-Peter Geis was probably the first geologist to recognize the Engebøfjell eclogite as a rutile deposit in the early '70's. He made a sampling profile through the Engebøfjellet road-tunnel.
1978-79	Additional sampling was done within a cooperation project between NGU and Elkem on rutile-bearing eclogites in Sunnfjord.
1979	Frank Barkve and Tore Birkeland focused on Engebøfjellet in an investigation of heavy rocks as breakwater material. That was the start of a long and complex process which resulted in Fjord Blokk's eclogite mining operation in 1995.
1984-85	Several companies were active at Engebøfjellet in the mid-80's investigating the rutile and breakwater material/aggregate possibilities.
1990	NGU made a W-E sampling profile along the deposit (Korneliussen and Furuhaug 1991).
1991	R. McLimans (DuPont), S. Parr (Stokke Industri) and A. Korneliussen (NGU) visited Engebøfjellet on a rutile/eclogite excursion in W. Norway, followed by a sample profile through the road tunnel later the same year by McLimans and K. Davies (also from DuPont).
1992	Signing of agreement between DuPont and NGU to jointly investigate the rutile potential of eclogites in W.Norway.
1995	Fjord Blokk and Conoco/DuPont made an agreement for a joint rutile investigation of Engebøfjellet, followed by core-drilling, beneficiation tests, surface sampling and geologic mapping activities. At first, the intent was to drill 400 m in the eastern part of Engebøfjellet near Fjord Blokk's quarry and financial support was given by the Prospecting Fund. The drilling started in October 1995. Shortly afterwards, the drilling program was extended.
1996-97	Continued investigations of the rutile potential incl. 15000 meters of core drilling, gravimetric investigations, structural and lithological mapping and mineralogical investigations

continuation from the leuco - transitional eclogite trend illustrated by the solid line in Fig. 25, and a «Ti-enriched ferro eclogite», illustrated by the stippled line in Fig. 24. It is believed that the reason for this split-up of the ferro eclogite is caused by crystal fractionation processes in the gabbroic protolith. The metamorphic influence is considered minor, although evidence for this interpretation is not documented. Thirdly, some ferro eclogite samples at approx. 18% Fe_2O_3 are distinctly enriched in P_2O_5 (0.5-2% P_2O_5 vs. the normal values of $<0.2\%$ P_2O_5), as shown in Fig. 25. This eclogite variety is called «P-rich ferro eclogite». Unfortunately no field-criteria has been developed to distinguish these ferro eclogite varieties in the field; at present they can only be recognised in terms of their chemical compositions. Amphibolite unit rocks, which are easily recognisable in the field, tend to be enriched in elements such as La

and Zr compared to the leuco-, transitional- and ferro eclogites, indicating a distinct precursor and/or a different geologic evolution.

Rutile is determined by the so-called *rutile analytical procedure* ($\% \text{ rutile} = \% \text{TiO}_2$ (analysed by XRF) - $\% \text{TiO}_2$ (dissolved in HCl; analysed by ICP)). In this procedure rutile is not dissolved while ilmenite is dissolved by HCl. Silicates are not dissolved in HCl, i.e. TiO_2 in silicates will come out as rutile by this method. The method is only to be used on rocks, such as eclogites, where TiO_2 in silicates are low enough to be neglected for practical purposes. In the typical Engebøfjell eclogite more than 90% of the titanium in the rock occurs as rutile. Those samples in Fig. 25 that plot well away from the line $\text{rutile}/\text{TiO}_2 = 1$ have a distinct portion of retrograde ilmenite formed during the deformational episodes D_3 , D_4 and D_5 . Microphotographs of ferro eclogite showing different stages of retrograde overprinting are shown in Figs. 26 & 27.

Table 3: Major lithologic units in the Engebøfjell - Vevring area.

The rocks enclosing the Engebøfjell eclogite body

Granitoid gneisses (undifferentiated)	The granitoid gneisses represent Proterozoic granitic and tonalitic plutonic rocks belonging to the Helle complex. They intruded into the mafic and felsic rocks of the Hegreneset complex and were extensively deformed by the Caledonian orogeny.
Amphibolite unit (undifferentiated)	This unit is characterised by cm- to dm-scale alternating mafic- and felsic bands. The mafic components are eclogitic to amphibolitic (retrograded eclogite) and the felsic component resembles tonalite or diorite. These rocks are now strongly deformed and metamorphosed due to the Caledonian orogeny. This unit represents an older part of the Hegreneset complex into which the Engebøfjell protolith gabbro intruded.

The Engebøfjell eclogite rocks

Leuco eclogite	Fine-grained eclogite with a fairly low garnet content. In varieties with minor deformation a gabbroic texture is preserved. <i>Leuco- and transitional eclogite</i> is distinguished from ferroeclogite by its leucocratic character incl. lower garnet content. The increase in iron and titanium values is gradual.
Transitional eclogite	Eclogite intermediate between the leuco- and the ferro eclogite.
Ferro eclogite	The ferro eclogite (ore type) is a relatively massive, dark, garnet-rich eclogite with a distinct rutile-content. A characteristic feature that is commonly seen is a series of thin cracks (D_5) in which the eclogite has been retrograded (amphibolitised). Occasionally 1-2 mm large holes after a leached-out mineral can be seen along certain zones in this eclogite.

Mineralogy: The Engebøfjell gabbroic protolith was metamorphosed under eclogite-facies P and T conditions of 15-17 kbar and ca. 600°C. Eclogitisation corresponds to a complete mineralogical change. No relict of magmatic silicate minerals was found in the Engebøfjell eclogite. The degree of textural equilibration of the eclogites is dependent on their deformational history during the eclogite-facies metamorphism (D_1 and D_2 phases). The leucocratic rocks show a textural evolution from coronites to foliated eclogites. In coronitic leuco eclogites (e.g. "massive leuco eclogite"), albite, together with phengite, zoisite and quartz, forms microcrystalline pseudomorphs after plagioclase. Small granular amphibole and clinopyroxene has replaced magmatic mafic phases. Coronas of garnet separate felsic and

mafic domains, underlining the former grain boundaries and the relict gabbroic texture. In more deformed rocks, segregations after plagioclase have become coarser-grained and taken an elongate shape; they contain paragonite, phengite and clinozoisite. The mafic matrix surrounding them is recrystallised into a fine-grained assemblage of garnet, clinopyroxene and amphibole. Completely recrystallized leuco eclogites are found at the deformed margins of the massive leuco eclogite body. The melanocratic rocks, with Ti ore potential, are generally completely recrystallized into foliated eclogites. On average, eclogites from Engebøfjellet are fine-grained rocks, either as a result of strong deformation (ferro eclogites) or lack of complete recrystallisation (coronitic leuco eclogite). Ferro eclogites are generally granular, with a grain size less than 0.5 mm.

Eclogite paragenesis comprises garnet, omphacite, amphibole, phengite, clinozoisite, quartz, dolomite, rutile and pyrite. Accessory minerals are apatite, allanite and zircon. Ti is now mainly residing in rutile, mostly as matrix grains (0.5 mm); a minor amount forms numerous but tiny inclusions within silicates. Discrete ilmenite grains are recorded in one sample. Modal as well as mineral chemical variations are found from ferro- to transitional and leuco- eclogites. Ferro eclogites are usually rich in garnet (from ca. 25% to 55%) and rutile (3-6%). Within this group, bulk-rock chemical variations are expressed by modal variations in garnet, clinopyroxene and amphibole as well as in minor phases like quartz, clinozoisite, phengite, rutile and apatite. Transitional eclogites show an increase in clinopyroxene (omphacite); large amphibole porphyroblasts are common. Within this group, coarser-grained eclogites contain omphacite porphyroclasts sheared within a fine-grained matrix of omphacite, garnet, amphibole, carbonate and mica. Leucocratic rocks are enriched in mica, clinozoisite, and often in amphibole and quartz; garnet forms generally less than 20% of the rock. Omphacite characteristically forms elongate porphyroblasts, up to 2-3 cm long. Some leuco eclogites are layered on the mm-cm scale and contain numerous phengite (carbonate-bearing quartz-rich layers). Concurrently with the modal changes, mineral compositions also evolve. The almandine garnet become richer in Mg (pyrope component), from Alm 56-65 Spe 1-5 Pyr 9-17 Gro 17-24 And 1-7 in ferro- and transitional eclogites to Alm 52 Spe 2 Pyr 24 Gro 21 And 2 in one leuco eclogite. Both clinopyroxene and amphibole show an increase in Al and Na, evolving from chloromelanitic omphacite (Jd 21-35) to omphacite (Jd 45) and from actinolitic hornblende to barroisite.

Fluid-rock interaction was frequent at all stages in the history of these rocks. The abundance of volatile-bearing minerals (mainly amphibole, phengite, clinozoisite, dolomite and apatite) characterizes eclogite-facies parageneses from Engebøfjellet. Amphibole is ubiquitous, in amounts ranging from trace to being the main Na- and Ca-bearing phase (40-50%). Dolomite is common, varying in abundance from a few scattered grains to a major phase. Abundant eclogite-facies veining (quartz, omphacite, garnet, carbonate, phengite...) indicate that the fluid pressure was high during this event.

Retrogression of the eclogites is often seen dependant on both deformation and fluid infiltration and occurred predominantly along shear zones and margins of the lens. Garnet amphibolites represent the first retrogression stage (D₃). Amphibolites within major shear zones (D₄) contain amphibole (hornblende type), epidote and plagioclase; garnet breaks down. Static retrogression of eclogites to symplectitic assemblages of the same minerals is observed in undeformed areas near these shear zones. The mineral assemblages indicate that the D₄ deformation occurred under conditions characteristic of the epidote-amphibolite facies. Local coronitic retrogression along late fractures and mineral filling in the veins (actinolite, epidote, chlorite, calcite, quartz, magnetite, ilmenite and/or titanite) represent a greenschist facies overprint (D₅). During retrogression, rutile is replaced by ilmenite along grain rim and

fractures. This transformation generally amounts to less than 10% in eclogites with minor retrogression but can reach more than 95% in totally amphibolitized samples. Only trace amounts of titanite occur in a few late D₅ veins or as thin coronas around rutile/ilmenite grains in extensively retrograded eclogites.

Structural geology. Deformation of the Engebøfjellet eclogite and the surrounding rocks may be separated into six stages, designated D₁ to D₆. Prior to deformation magmatic layering(?) may have existed in the rocks. Metamorphic conditions and mineralogy for this primary phase can not be established due to later, overprinting metamorphic events. The first observable stage, D₁, is shown as isoclinal folds (F₁) of the mineralogical banding in the protolith rocks. A dominant transposition foliation (S₁), often parallel to this banding, was developed. Metamorphic conditions during the first stage of deformation probably reached eclogite facies, as indicated by formation of garnet and omphacite (Carswell, 1990; Yardley, 1989). Orientation of the F₁ axes, which have a subhorizontal, E-W orientation, may be explained by N-S shortening. However, later non-coaxial deformation, with potential rotation, make any conclusion speculative.

After formation of the S₁ foliation, an elongated omphacite formed in the eclogite rocks (post-D₁). Since this mineral has grown superimposed on to the foliation, and with a random orientation, it probably relates to a period of static P conditions.

During the following D₂ stage, the S₁ foliation is folded into tight to isoclinal F₂-folds. In these structures, a spaced cleavage generated near the fold-hinges. In the F₂ fold-limbs, which suffered the most D₂ strain, a new penetrative foliation (S₂) was formed. This foliation, which is very fine grained and mylonitic(?), represents the dominant fabric in the Engebøfjellet Eclogite. One good example of a F₂-fold is illustrated in cross-section D-D' (Fig. A4.2 in Korneliussen et al. 1998), whereas the Fureåsen area (see Appendix 2 in Korneliussen et al. 1998), near the top of Engebøfjellet, shows well exposed outcrop-scale structures. Metamorphic conditions during the D₂ stage reached eclogite facies, as suggested by the stable minerals garnet+omphacite along the S₂ foliation. Field observations of kinematic indicators in the D₂ high strain zones reveal both dextral and sinistral shear-sense for separate zones, respectively, i.e. parallel to the WNW-ESE lineation. One way to interpret this pattern is that the eclogite body suffered regional, coaxial N-S shortening during the D₂ phase.

The following D₃ stage folds the S₂ foliation into tight F₃-folds. A spaced cleavage formed in the hinges of these folds, whereas distinct meter-wide shear-zones (S₃) generate in the fold-limbs. At other places, the eclogitic S₂ foliation is reactivated as shear-zones. In both cases the eclogite is retrograded into (garnet-) amphibolite. Growth of amphibole+garnet+plagioclase in these late high-strain zones indicate amphibolite facies, garnet zone metamorphic conditions (Yardley, 1989) during the D₃ stage.

The D₄ stage is characterized by the formation of meter-wide shear zones (S₄), which have been observed at a few locations. One of these structures cuts through the F₃ fold in the quarry (described above); thus it post-dates the F₃-folding. Along the margin of the S₄ high-strain zones, the eclogite is retrograded into amphibolite, whereas the shear-zones contain amphibole+plagioclase(?)+biotite+epidote+quartz. The lack of garnet, and growth of biotite, suggest that these shear-zones formed under epidote-amphibolite to upper greenschist facies, and biotite zone conditions (Yardley, 1989), maybe from a progressive continuation of the D₃ stage.

Shear-sense indicators (e.g., Hamner and Passchier, 1991) for both the D₃ and D₄ stages, such as composite shear fabrics, shear-folds and wings around mechanical strong bodies, support non-coaxial sinistral shear. This movement was subhorizontal, parallel to the

stretching lineation, and resulted in internal shortening by stacking and folding of the first order lens. Thus, the deformation mechanism probably was sinistral transpression.

The S_4 shear-zones and all older structures are truncated by sub-vertical N-S striking joints of the D_5 stage. These joints are filled with epidote + quartz (+ carbonate + chlorite), whereas the wall-rocks often show cm-wide zones where omphacite+ blue amphibole+garnet is replaced by green amphibole. These mineral associations indicate epidote-amphibolite to greenschist facies conditions during the D_5 stage. The N-S, vertical orientation of the fractures, and their tensile nature, suggest that this deformation relates to N-S, horizontal shortening.

It is worth to mention that similar fractures are found in eclogites several km south of Engebøfjellet. There, steep tensile fractures strikes NW-SE. This change in orientation from N to S may relate to late, open folding in the area; folds that possibly are associated with W-directed movement in the detachment zone. These folds are suggested to have a late Devonian - Early Carboniferous age (e.g. Torsvik et al. 1987). Thus, these late, tensile fractures constitute a possible marker that may help to establish late-/post-Caledonian folding of the Precambrian basement.

The last deformation observed in the rocks, the D_6 stage, is present as two populations of brittle faults: (i) N-S striking, moderately to steeply east and west dipping normal faults, and (ii) sub-vertical, NNW-SSE and NE-SW striking strike-slip faults. Slip on the faults is indicated by separation of markers in the rock, as well as lineations on the slip-surfaces (slickensides). These kinematic indicators suggest formation of the faults during N-S shortening, which triggered E-W extrusion/extension. Greenschist facies or lower P-T conditions during the D_6 stage is suggested from the brittle style of deformation. This type of structures are suggested by Braathen (1998) to reflect Carboniferous - Permian deformation in the region.

The suggested deformation sequence and its tectonic implications is important in a regional perspective. The steep E-W orientation of foliations (S_2 and S_3) seen in the Engebøfjell area are not continuous to the E. There, the main foliation successively changes to moderate N dips. However, the high-strain zone of Engebøfjellet appears to be continuous into the eastern area. Thus high-strain zone bounds an open box-like antiform further S, which has an other high-strain zone as its southern margin. Internal foliation in the antiform probably predates the shearing in the fold-limbs. In the Fureviknipa area W of Førde, a distinct fold-pair is evident. The southern antiform is open and upright, and is probably truncated by the detachment zone, whereas the synform further N is tight and S-verging. The upper limb of the synform reveals a high-strain zone that may correlate with the Engebøfjell shear-zone.

Thus, at least two old foliations can be distinguished in the regional map-pattern, in addition to the mylonitic foliation in the detachment zone. The oldest foliation, which could be Sveconorwegian in age (1000-1200 Ma), occurs in hinge-areas of regional folds. There, isoclinal sheet-like folds within the foliation indicate that significant strain affected the rock at this stage, and that primary, possibly older structures were transposed. A younger foliation is superposed on the older fabric in high-strain zones that are found in the fold-limbs. This foliation, which can be correlated with the S_3 and/or S_4 fabric of Engebøfjell, reveals subhorizontal stretching lineations, whereas shear-sense indicators suggest sinistral shear. Eclogites and eclogite facies fabrics, probably Caledonian in age (Andersen and Jamtveit 1990), are retrograded into amphibolite-facies rocks in the D_3/D_4 high-strain zones. This faulting/shearing occurred at significant crustal depths. If this reasoning is valid, then sinistral transcurrent movements occurred on moderate to steeply dipping shear-zones at some stage of the Caledonian orogeny of Western Norway.

In summary – Engebøfjellet geology:

The Engebøfjellet eclogite deposit is situated at the northern side of Førdefjord near the small community Vevring in Naustdal kommune, Sogn og Fjordane county. Geologically the Førdefjord area belong to the «Western Gneiss Region», between the Devonian Kvamshesten basin to the south and the Devonian Håsteinen basin to the North. Recent mapping divide the Førdefjord region into two major geologic units: the Hegreneset complex and the Helle complex. The Hegreneset complex (oldest) contains a variety of amphibolitic, eclogitic and gabbroic rocks, together with tonalitic to dioritic gneisses. The Helle complex comprises mainly granitic and granodioritic gneisses.

The Engebøfjellet eclogite is a 2.5 km long, complexly deformed, lens-formed body surrounded by hybrid mafic-felsic country-rocks belonging to the Hegreneset complex. The protolith to the eclogite is believed to be a Fe and Ti-rich Proterozoic gabbroic intrusion, recently zircon-dated at 1500 Ma (T. Krogh, pers. comm.). The transformation into eclogite is related to Caledonian high-pressure metamorphism at approx. 400 Ma. In this process, ilmenite in the gabbro protolith was replaced by rutile. The Ti-enriched part of the eclogite is now rutile ore.

The eclogite mineralogy is closely related to structural and metamorphic events. Two eclogite facies deformation events (D_1 and D_2), two amphibolite facies events (D_3 and D_4), one amphibolite to greenschist facies event (D_5) and one late brittle fault event (D_6) under lower greenschist conditions, are recognised. Rutile is affected by the D_3 , D_4 and D_5 events by the alteration to ilmenite and also to titanite (mainly D_5), while the effect of D_6 is insignificant.

Engebøfjellet is one of the most extensively drilled eclogites in the world, and approx. 15.000 meters of cores are available. These cores represent a unique material for geological, petrological and mineralogical research on the eclogite itself as well as its relations to metamorphic and structural episodes and to the country-rocks. Continued research on the genesis of the Ti-ore will inevitable lead to new data that can be used in the ore-evaluation work. Extensive geologic knowledge of Engebøfjellet and its geologic surroundings might stimulate to the development of effective exploration methods to discover other Ti-rich eclogites in the Førdefjord area and elsewhere.

To establish a good geological model for the Engebøfjellet eclogite and its surroundings, a dynamic process needs to be developed which takes account to a complex set of interrelated parameters. For example, the mineralogy is strongly affected by structural and metamorphic episodes, and the variations in the metamorphic character within the eclogite are related to structural episodes which have channeled the flow of metamorphic fluids and allowed the reequilibration of mineral assemblages to happen.

6. THE STEINKORSEN ECLOGITE

A regional gravimetric survey by NGU on the northern side of Førdefjord in 1998 identified a series of gravity anomalies between Engebø in the west and Naustdal in the east (Elvebakk et al. 1999). Of these anomalies particular interest is related to one anomaly in the Steinkorsen area 3 km N of Førdefjord and 10 km E of Engebøfjellet. The data showed that this anomaly is caused by a large body of dense rock at depth. Of the known rocks in the area only eclogite is dense enough for this kind of anomaly. The geographic position of the Steinkorsen anomaly area and the preliminary interpretation of a possible eclogite body in a vertical profile, is shown in Fig. 31.

In order to obtain more precise information additional geological and gravimetric work was done in 1999. Field-photographs taken in the Steinkorsen area and microphotographs of some of the samples taken, are shown in Figs. 31 and 32. Geologic observations in the anomaly area show that a significant amount of eclogite and amphibolite (retrograded eclogite) is outcropping. Most of this eclogite/amphibolite (70-80% of the outcropping eclogite) have a low TiO₂-content (1-2 % TiO₂); the rest of the outcropping eclogite is Ti-rich (3-5% TiO₂).

A series of chip-samples were taken and later analysed by the X-Met portable XRF. Average values for the individual chip-sample sets are given in Table 1 and the results plotted in Fig. 30. The plot show a distinct bimodality in Fe₂O₃ – TiO₂ content with two eclogite varieties, one TiO₂-rich (ore-type) and one with low TiO₂-content. This is similar to the Fe₂O₃-TiO₂ pattern for Engebøfjellet shown in Fig. 26.

Fig. 31 shows the results of X-Met analyses of a 30-40 kg sample taken at locality K148.99. This eclogite is fine-grained.

The eclogite/amphibolite is significantly deformed under eclogite-facies conditions as well as under amphibolite facies which has resulted in distinct alteration of the eclogite to amphibolite.

The outcropping eclogite strengthens the argument that the source at depth of the density anomaly is a large eclogite body. Presumably the protolith of this body was a gabbroic intrusion. The occurrence of Ti-rich eclogite in the anomaly area, represented by eclogite localities such as K141.99, K147.99, etc, indicates that the protolith has experienced fractionation processes leading to Ti-enrichment. It is probable that the underlying eclogite body contains significant tonnages of rutile-rich eclogite with 3-5 % TiO₂ as well as significant amounts of eclogite with less than 3 % TiO₂. *Core-drilling is needed to obtain exact information of the character and rutile content of the eclogite body at depth.*

Due to the large similarity between the Steinkorsen and the Engebøfjellet eclogites, the geological description of Engebøfjellet given in Chapter 4 is to a large extent also valid for Steinkorsen.

Comments to the gravity data presented in the reports by Elvebakk et al. (1999) and Dalsegg et al. (1999)

The gravity profiles give a rough impression of the density anomalies in the mountainous area between Redalsgrend 3-4 km East of Engebøfjellet and Naustdal. The gravity anomaly pattern in the residual gravity map from this area is shown by Dalsegg et al. (1999), which is an updated version of a similar map by Elvebakk et al. (1999). This anomaly pattern is caused by density variations in the underlying rocks. The interpretation of these density variations in terms of blocks of heavy rocks along a number of gravity profiles, are shown by the various interpretation models in the two

reports (see comments below). The present interpretations are not necessarily correct; in most cases a complex combination of irregular blocks with different densities will give a more correct picture of the situation. They need to be further refined to be more in accordance with geological observations and interpretations.

Based on specific gravity the following subdivision can be done of the rocks in the area:

- Granitoid gneisses: 2700-2800 kg/m³
- Amphibolites: 2800-3100 kg/m³
- Low-Ti eclogites: 3100-3300 kg/m³
- Ti-rich eclogites: 3300-3500 kg/m³

Comments on the gravity profiles measured in 1998 (Appendix 4 in Elvebakk et al. 1999):

- **P1b** crosses the central part of the Naustdal village eclogite body. The residual bouguer anomaly is significant, confirming a previous assumption that this eclogite continues to several hundred meters depth. The present model uses two bodies at 3400 kg/m³ to explain the residual bouguer field (RBF). A more correct model would probably be to combine various irregular blocks with different densities ranging from 3200 to 3400 kg/m³ into one large, heterogeneous eclogite body.
- **P1a** passes the western end of the outcropping part of the Naustdal eclogite. The small gravity anomaly and the corresponding small and shallow eclogite model confirms the field observation that the eclogite is thinning out westwards.
- **P10-8** (0.5-1 km W of P1a) shows only minor variations in RBF, which can be explained by a number of small eclogite bodies.
- **P5** (3-4 km W of Naustdal) in the Steinkorsen area, has a major RBF anomaly which in this model is explained by a large lens-like 3400 kg/m³ block (eclogite) reaching from the surface at approx. 660 m.a.s.l. to below sea-level. It is probable that this block represent a major eclogite body similar to the Naustdal eclogite or the Engebøfjellet eclogite further west.
- **P6** (1 km W of P5) has a RBF anomaly which is weaker than the P5-anomaly. Only minor zones of eclogite has been observed on the surface along this profile, and the reasons for the RBF-anomaly pattern must be at dept, for example as a combination of dense bodies as indicated on the model.
- **P7** (1 km W of P6) has relatively small RBF anomalies which might be explained by a combination of dens bodies as indicated on the profile. However, only low-Ti eclogites and amphibolites have been observed in the field in the respective anomaly areas; it might therefore be more correct to revise the present model by a combination of slightly less dense bodies.
- **P4** (W of P7) crosses a large low-Ti eclogite (partly amphibolitic) in the Bygdahaugen area. The flat-lying character of the 3300 kg/m³ body in the profile is consistant with the field observations. In a revised model this body might be replaced by a body with density 3200 kg/m³ to be more in accordance with the character of the exposed eclogite.
- **P3** (W of P4) crosses an area with large amounts of mixed amphibolitic rocks, minor eclogitic zones/bodies, and grey gneisses in various variations which have been given n average density at 3000 kg/m³ in the model.
- **P2** (W of P3) crosses the same rock units as P3 and the RBF can be explained as shown in the model.

Comments on the follow-up gravity profiles done in 1999 (Appendix 4 in Dalsegg et al. 1999):

- **P11** (E of P5) is at the eastern margin of the Steinkorsen gravity anomaly (map no. 99.124-03). A dens body at depth is needed to explain the measured RBF. Since surface observations in the Steinkorsen area in July 1999 showed that the outcropping eclogites in the area varies from low-Ti eclogite varieties (partly amphibolitic) to rutile-rich eclogite, the density variation for the eclogites in the area is assumed to vary from 3.1 to

3.5 kg/m³. Thus the anomaly source must be much more complex than indicated in the present model; it should incorporate both 3200 and 3400 kg/m³ bodies. The new complex body would then be larger than the present model body, and it should reach the surface to fit in with the eclogite on the geological map.

- **P12 - alternative I** (W of P5) involves two major dens bodies at 200-500m depth and some thin eclogite horizons reaching the surface. Since a significant portion of the eclogite found in the area has a fairly low titanium content (and low in iron), a more realistic model should include bodies at 3200 kg/m³ as well. This would increase the total volume of eclogite in the area.
- **Fig 12 - alternative II** involves one large dens body at depth instead of two bodies in alternative I. This indicates that many model alternatives can explain the measured RBF. Detailed geological information, such as drill-core information, is needed to take a significant step forward in the gravity modelling.
- **P13** (W of P6) has a weak RBF pattern that can be explained by a combination of dens bodies at depth. In the further refinements of this model a combination of 3200 and 3400 kg/m³ bodies should be used, some of these should reach the surface to fit in with observed eclogite zones in the field.
- **P14** (W of P7) has a weak RBF pattern that can be explained as shown in the model. In revised versions of this interpretation the flat-lying body with 3300 kg/m³ should be replaced with a body at 3200 kg/m³.
- **P15** (E of P16) has not been interpreted due to its flat RBF signature.
- **P16** (E of P1b) has a relatively flat-lying RBF pattern that can be explained by a number of small bodies. In revised versions of the model bodies at 3200 kg/m³ should be included.

Table 4: Chip-samples, Steinkorsen. Each values in the table is an average of individual analyses of 5-10 sub-samples analysed by the X-Met portable XRF.

Sample no.	TiO ₂	Fe ₂ O ₃	Sample no.	TiO ₂	Fe ₂ O ₃
K140.99	3.08	14.92	K146.99	1.37	10.82
K141.99	4.88	15.86	K147.99	3.18	15.04
K142.99	0.57	5.73	K148.99	4.46	17.15
K143.99	1.63	13.71	K149.99	3.31	16.46
K145.99	1.06	8.54			

7. VARIATIONS IN OXIDE GRAIN-SIZE

Image processing and characterisation of the oxide minerals based on low-resolution digital images from a video-camera connected to an optical microscope has been done on approx. 120 thin-sections from various deposits and deposit types. This is a fast method that gives a rough overview of the grain-size characteristics.

8.1. Image processing and characterisation of the titanium minerals based on optical images

The following equipment and methods is used for the image processing of the thin sections:

- Olympus polarising microscope and a 1.25x objective in reflected light.
- A JVC analogue RGB video camera, connected to a PC with a framegrabber.
- KS 300 image processing software from Carl Zeiss vision.

The method for the acquisition and processing of digital thin section images is as follows:

A digital image of the thin section is captured with the video camera, framegrabber, and KS software. The illumination on the microscope is set to a level where best possible discrimination is achieved between ilmenite + rutile versus pyrite. The result is a digital colour image. By varying the threshold levels for the colours it is possible to select the oxides (in this case ilmenite and rutile) and produce a binary image where (ideally) all ilmenite and rutile is show as white areas and all other minerals are black. This binary image has to go trough several steps of improvement, such as the removal of noise (all objects below a certain boundary level is scraped).

The result should be a binary image where white areas correspond to the areas of oxides (ilmenite and rutile) in initial the colour image.

The KS program can perform a variety of measurements of the binary image, such as

- Field measurement where the total percentage of minerals is calculated.
- Region measurements; where size and other morphological features (see below) of every single individual oxide grain is calculated.

With the 1.25x magnification, approx. 40% of a standard thin section is covered by one image. Each half of every thin section was measured and the results aggregated. In this way we can cover about 80% of a standard thin section. A macro in KS program designed for this particular type of measurements, facilitates the measurements rapidly. The data generated is then copied into a Excel worksheet for further processing and presentation.

For the region measurement (measurement of each single grain) the following parameters were calculated, as named by the KS program:

AREA: The area in μm^2 of the individual grain.

AREAF: The filled area in μm^2 inclusions is then regarded as part of the grain.

ELLIPSEA: The longest axis in μm of an ellipse with the same geometric moment of inertia as the object.

ELLIPSEB: The shortest axis of the ellipse

FERETMAX: The maximum *Feret* diameter (μm), i.e. the maximum distance between two parallel opposing tangents on the measured object.

FERETMIN: The corresponding shortest *Feret* diameter.

DCIRCLE The diameter in micron of an circle with the same area as the object and measured in AREAF. Mathematically DCIRCLE is defined below. The parameter DCIRCLE gives an easy comparable value which excludes all difference in particle shape.

$$DCIRCLE = 2 \sqrt{\frac{AREAF}{\pi}}$$

For the field measurements, the area percentage (see example in table 3) is calculated in 7 different steps, to give data on the percentage distribution grains of different sizes. Thus we have percentage data on:

- Total percentage
- Percentage of grains with DCIRCLE < 50 μm
- Percentage of grains with 50 > DCIRCLE < 100 μm
- Percentage of grains with 100 > DCIRCLE < 150 μm
- Percentage of grains with 150 > DCIRCLE < 200 μm
- Percentage of grains with 200 > DCIRCLE < 250 μm
- Percentage of grains with DCIRCLE > 250 μm .

Sources of error

There are several types of error and approximations which occur in these type of image processing measurements. First and most important is the lack of contrast between different minerals. When two minerals have almost the same colour, its not possible to discriminate between them. This is a particular problem with ilmenite and rutile, which are regarded the same in our measurements here. Oxidised pyrite (if present) often cannot be discriminated from the oxides (ilmenite and rutile) by this procedure, in such cases the results will be wrong. In most cases, however, the error caused by oxidised sulphides is negligible.

Another source of error is the noise removal. At 1.25x magnification, 1 pixel equals an object of 17 micron size. By removal of all noise equal and less that 1 pixel, every real object less that 17 microns is also lost. This source of error can be reduced by doing the measurements under higher magnification, but this again would make the measurements far more time consuming. The removal of noise results in somewhat stronger grain-distribution diagrams (e.g. Fig. 38). All grain distribution curves converges in a minimum grain-size of approx. 30 microns which is the pixel-size for noise removal. Consequently, all the small oxides grains below this size is lost from the calculation.

A third error is that objects (mineral grains) that cut the image frame is measured with wrong shape. This is error can be avoided by omitting all objects that cut the image frame from the measurements.

8.2. Image processing and characterisation of titanium minerals based on SEM-images

Methods

Three selected thin sections were sent to SEM for elemental mapping. This process records the records distribution of 16 elements (Al, Ca, Cl, Cu, F, Fe, K, Mg, Mn, Na, P, S, Si, Ti and Zn) each recorded on an individual image file (greyscale image). Together with a backscatter electron image (BSE), these elements maps are used for image processing. NGU presently uses the KS 300 image processing software from Carl Zeiss vision.

The image processing involves the following steps:

- (1) From the important (in our case Ti, Fe, P and S) element maps binary images are produced.
- (2) The binary images are processed to remove noise.
- (3) The binary images are then combined and processed by several steps of *Boolean* operations, the results is a set of binary images which corresponds to the distribution of ilmenite, rutile, apatite and pyrite.
- (4) The percentage of each mineral is recorded
- (5) Each of these mineral images are given a special colour from special designed *look up tables* and merged on to the BSE image.
- (6) The result is a set of BSE images where the distribution of ilmenite, rutile, apatite and pyrite is shown with individual colours (Fig. 36)

Macros in the KS system facilitates and repeat the image processing quickly.

Limitations and errors

The SEM elemental mapping gives an very accurate map of the distribution of the selected elements on the thin sections. The method however have the following disadvantages and errors:

- (1) Expensive, the SEM running time is 16 hours, the image processing is about 0.5 hours for each section. Presently only the SEM running cost is about 270 US\$ per thin section.
- (2) With our system set-up on a small area (1.3 x 1.3 cm) of a thin section is analysed. The pixel size is about 3 microns and this is the smallest size of any object to be measured under ideal conditions (that is no noise).

However the final results is far more accurate than optical microscopy image processing and is the only method where accurate discrimination between ilmenite, rutile, apatite, and pyrite can be done.

8. ON THE VARIATION IN RUTILE GRAIN-SIZE

A selection of thin-sections from various rutile deposits and provinces were investigated by image processing via the optical image processing procedure described in chapter 6.1. This processing has resulted in two data-sets: one is the basis for cumulative grain-size distribution curves such as the example in Fig. 36. The data for these curves are stored in the table "OxideGrainData" in the rutile database and is not printed out as appendix in this report due to its large amounts of data (approx. 50.000 lines). The cumulative graph in Fig. 36 is an

example of a plot from this data-set. The other data-set consists of numbers for areal% (\approx vol.%) oxides in various grain-size intervals. These data are printed out in Appendix 4. The histogram graph in Fig. 36 is an example of a plot from this data-set. All the combined cumulative and histogram plots made can be seen in Appendix 5. A4-format photocopies of thin-sections are shown in Appendix 6, while Appendix 7 give an overview of microphotographs available in digital form in the CD of Appendix 8.

These data show a significant variation in mineralogical characteristics within individual deposits as well as between deposits and provinces. Particularly large variations in grain-size distribution can be seen in the Ødegård deposit in the Bamble region (Table 5a) from which a significant number of thin-sections have been investigated.

Average grain-size data from the various provinces do also show large variations. When comparing the > 250 microns interval, the Bamble region has 57.7 areal % (= vol. %) larger than 250 microns in average, the Bergen region 55.5 %, the Dalsfjord region 34.9 %, and the Førdefjord region 13.3 %. Within the Førdefjord region the Engebøfjellet and Steinkorsen deposits have 12.2 and 11.3 % of the oxides larger than 250 microns, respectively. According to these data rutile from the Førdefjord eclogite deposits are the most fine-grained in Norway.

Table 5: Grain-size distribution data (intervals) based on Appendix 4.

Grain-size summary

Locality	Grain-size intervals in microns (% oxides norm. to 100 %)						Sum
	< 50	50-100	100-150	150-200	200-250	> 250	
Average Bamble region:	1.9	13.0	10.1	9.0	8.3	57.7	100.0
Average Bergen region:	2.8	13.2	11.9	8.9	7.8	55.4	100.0
Average Dalsfjord region:	3.5	27.3	17.1	10.5	6.6	34.9	100.0
Average Førdefjord region:	5.7	36.6	23.0	13.5	7.5	13.5	100.0
Average for the Ødegård deposit:	2.6	17.4	11.9	9.8	9.1	49.3	100.0
Average for the Husebø deposit (Bergen region):	3.7	16.7	15.3	9.3	8.3	46.5	100.0
Average for the Ramsgrønova deposit (Dalsfjord region):	1.3	12.3	9.5	7.8	8.0	61.2	100.0
Average for the Engebøfjellet deposit (Førdefjord region):	6.5	35.3	22.3	15.0	8.3	12.2	100.0
Average for the Steinkorsen deposit:	7.5	38.5	23.3	13.3	5.8	11.3	100.0

Table 5a: Grain-size data for samples from the Bamble province. The grain-size distribution numbers are normalised to 100%.

The Bamble region

Locality	Sample	Grain-size intervals in microns (% oxiders norm. to 100 %)						Sum
		< 50	50-100	100-150	150-200	200-250	> 250	
Fone	KB5E.91	0.6	4.7	5.3	15.8	11.7	62.0	100.0
Gjerstadvatnet	KB43A.91	0.2	2.7	3.1	2.7	4.1	87.2	100.0
Haukåsen	KB9.91	0.7	2.1	3.5	5.0	10.6	78.0	100.0
Krefjell	KB8A.91	0.2	1.5	1.7	1.9	1.7	93.1	100.0
Krefjell	KB8B.91	0.0	0.6	1.1	0.3	0.8	97.2	100.0
Laget	KB10A.91	1.8	6.1	3.1	6.1	0.0	82.8	100.0
Lindvikkollen	KB11B.91	0.6	5.7	11.1	10.0	11.6	61.0	100.0
Løfthaug	KB1A.91	0.7	8.4	14.4	12.0	11.0	53.5	100.0
The Ødegården deposit	1Ø/26.15	0.0	2.7	1.4	0.0	0.0	95.9	100.0
The Ødegården deposit	1Ø/35.30	0.3	4.0	7.7	12.4	8.8	66.8	100.0
The Ødegården deposit	1Ø/5.40	1.0	7.5	7.0	6.8	6.8	70.8	100.0
The Ødegården deposit	1Ø/50.20	1.2	7.8	10.4	11.3	9.6	59.7	100.0
The Ødegården deposit	1Ø/67.25	1.4	12.3	16.1	12.0	14.0	44.2	100.0
The Ødegården deposit	1Ø/9.40	2.5	10.8	8.8	7.3	7.9	62.7	100.0
The Ødegården deposit	2Ø/26.60	3.8	13.6	15.4	15.9	10.4	40.9	100.0
The Ødegården deposit	2Ø/28.70	2.4	16.8	20.1	13.7	13.0	34.0	100.0
The Ødegården deposit	2Ø/29.30	3.8	24.4	21.8	16.9	14.8	18.2	100.0
The Ødegården deposit	2Ø/29.90	10.9	29.8	18.9	13.6	11.3	15.4	100.0
The Ødegården deposit	2Ø/30.15	2.2	13.3	15.9	14.5	11.7	42.5	100.0
The Ødegården deposit	2Ø/32.15	0.3	2.7	3.3	4.7	2.0	87.0	100.0
The Ødegården deposit	2Ø/32.25	0.8	3.1	1.6	2.8	1.3	90.5	100.0
The Ødegården deposit	2Ø/34.55	7.3	35.1	20.9	14.0	4.0	18.7	100.0
The Ødegården deposit	2Ø/48.10	7.1	51.8	23.2	7.1	10.7	0.0	100.0
The Ødegården deposit	2Ø/51.90	0.0	3.7	11.1	4.9	3.7	76.5	100.0
The Ødegården deposit	2Ø/58.45	0.5	3.8	13.5	8.7	6.3	67.3	100.0
The Ødegården deposit	2Ø/6.20	3.1	19.0	22.7	16.8	18.8	19.6	100.0
The Ødegården deposit	2Ø/61.65	9.1	27.3	13.6	22.7	27.3	0.0	100.0
The Ødegården deposit	2Ø/67.90	0.0	1.8	2.1	2.1	9.1	84.8	100.0
The Ødegården deposit	2Ø/68.30	0.0	100.0	0.0	0.0	0.0	0.0	100.0
The Ødegården deposit	2Ø/77.90	1.0	9.7	14.8	16.3	14.3	43.9	100.0
The Ødegården deposit	2Ø/81.41	2.5	19.0	10.7	5.5	1.6	60.7	100.0
The Ødegården deposit	2Ø/85.45	1.1	4.0	7.6	5.8	8.7	72.7	100.0
The Ødegården deposit	2Ø/91.45	2.2	10.9	9.5	8.8	10.2	58.4	100.0
Ødegården 2	KB12.91	0.6	5.9	11.0	15.2	13.1	54.2	100.0
Ødegården 2	KB12J.91	0.7	8.0	10.4	8.5	8.3	64.0	100.0
Ødegården 5	KB37A.91	0.7	8.4	14.4	12.0	11.0	53.5	100.0
Øydegårdsvatnet	KB14C.91	0.8	4.6	4.4	5.2	5.7	79.3	100.0
Alverstrømmen	KH50A.89	0.0	1.0	1.0	0.8	0.6	96.2	100.0
Average Bamble region:		1.9	13.0	10.1	9.0	8.3	57.7	100.0
Average for the Ødegård rutile deposit:		2.6	17.4	11.9	9.8	9.1	49.3	100.0

Table 5b: Grain-size data for samples from the Bergen province. The grain-size distribution numbers are normalised to 100%.

The Bergen region

Locality	Sample	Grain-size intervals in microns (% oxides norm. to 100 %)						Sum
		< 50	50-100	100-150	150-200	200-250	> 250	
Askeland	KH52B.89	4.0	21.0	20.0	11.3	9.4	34.7	100.0
Buldrevika 3	KH59.89	5.0	16.0	9.0	10.3	11.4	48.6	100.0
Buldrevika 3	KH60.89	5.0	25.0	13.0	13.3	9.8	33.1	100.0
Havrevåg	KH14A.89	1.0	4.0	5.0	3.7	2.9	82.7	100.0
Havrevåg 2	KH17.89	2.0	9.0	11.0	7.2	9.8	62.1	100.0
The Husebø deposit	KH2A.89	3.0	16.0	16.0	9.4	12.0	43.4	100.0
The Husebø deposit	KH2B.89	5.0	17.0	14.0	11.2	4.9	48.0	100.0
The Husebø deposit	KH2C.89	3.0	17.0	16.0	7.4	8.2	48.2	100.0
Kårbø	KH22.89	3.0	16.0	16.0	10.9	14.9	39.8	100.0
Odland 2	KH62A.89	3.0	14.0	14.0	17.1	17.8	34.5	100.0
Odland 2	KH62C.89	8.0	35.0	26.0	15.2	6.7	9.4	100.0
Odland 3	KH62.89	3.0	9.0	7.0	4.7	5.5	71.1	100.0
Sætrevik Ø	KH63A.89	3.0	12.0	11.0	7.6	6.6	61.0	100.0
Sætrevik Ø	KH63B.89	1.0	6.0	11.0	12.0	9.5	60.2	100.0
Sætrevik Ø	KH63E.89	5.0	25.0	20.0	14.7	8.3	26.4	100.0
Ådnefjell	KH54B.89	6.0	24.0	22.0	10.3	6.6	30.5	100.0
Ådnefjell	KH54C.89	1.0	9.0	9.0	8.6	7.0	65.2	100.0
Ådnefjell	KH54D.89	1.0	8.0	9.0	7.5	5.7	68.7	100.0
Ådnefjell	KH55.89	0.0	3.0	4.0	2.5	4.0	86.4	100.0
Ådnefjell 4	KH56A.89	1.0	7.0	9.0	6.0	6.7	70.7	100.0
Ådnefjell 4	KH56B.89	1.0	10.0	9.0	7.9	4.5	67.7	100.0
Ådnefjell 4	KH56C.89	2.0	11.0	10.0	6.2	6.9	64.2	100.0
Ådnefjell 4	KH56D.89	1.0	5.0	6.0	5.3	5.7	77.3	100.0
Ådnefjell 4	KH56E.89	1.0	7.0	6.0	6.0	6.3	73.4	100.0
Ådnefjell 4	KH56F.89	1.0	5.0	5.0	6.5	3.8	77.7	100.0
Average Bergen region:		2.8	13.2	11.9	8.9	7.8	55.4	100.0
Average for the Husebø rutile deposit:		3.7	16.7	15.3	9.3	8.3	46.5	100.0

Table 5c: Grain-size data for samples from the Dalsfjord province. The grain-size distribution numbers are normalised to 100%.

The Dalsfjord region

Locality	Sample	Grain-size intervals in microns (% oxides norm. to 100 %)						Sum
		< 50	50-100	100-150	150-200	200-250	> 250	
Botnatjørna	K292.94	6.0	33.0	22.0	17.4	5.8	15.3	100.0
Botnatjørna-East	K295C.94	6.0	33.0	27.0	10.9	5.0	17.9	100.0
Djupevatnet	K227A.94	4.0	42.0	12.0	7.7	0.0	34.6	100.0
Djupevatnet	K227B.94	3.0	29.0	16.0	13.3	10.1	29.1	100.0
Djupevatnet	K227E.94	3.0	41.0	32.0	12.0	6.0	6.0	100.0
Djupevatnet	K227F.94	1.0	12.0	10.0	13.2	8.1	55.7	100.0
Hestegardsnova	K291.94	11.0	52.0	20.0	5.6	0.0	11.2	100.0
Hovlandsvatnet	K301.94	3.0	15.0	11.0	11.8	10.1	48.8	100.0
Ramsgrønova	K222A.94	1.0	11.0	8.0	9.0	11.4	59.6	100.0
Ramsgrønova	K222C.94	2.0	20.0	14.0	7.6	6.3	50.2	100.0
Ramsgrønova	K222D.94	1.0	9.0	7.0	4.1	4.9	74.9	100.0
Ramsgrønova	K222D1.94	1.0	9.0	9.0	10.6	9.3	60.0	100.0
Ramsgrøvatnet	K272.94	1.0	30.0	24.0	12.3	8.7	23.5	100.0
Sagevika	K283.94	6.0	46.0	28.0	11.1	6.8	1.9	100.0
Average Dalsfjord region:		3.5	27.3	17.1	10.5	6.6	34.9	100.0
Average for the Ramsgrønova deposit:		1.3	12.3	9.5	7.8	8.0	61.2	100.0

Table 5d: Grain-size data for samples from the Førdefjord province. The grain-size distribution numbers are normalised to 100%.

The Førdefjord region

Locality	Sample	Grain-size intervals in microns (% oxides norm. to 100 %)						Sum
		< 50	50-100	100-150	150-200	200-250	> 250	
Botnarusta	K303.94	3.0	30.0	25.0	19.0	14.5	8.6	100.0
The Engebøfjellet deposit	1/126.5	5.0	40.0	31.0	11.1	7.7	4.4	100.0
The Engebøfjellet deposit	13/140.0	10.0	49.0	24.0	12.7	3.1	0.8	100.0
The Engebøfjellet deposit	13/156.0	8.0	48.0	25.0	10.7	5.6	2.2	100.0
The Engebøfjellet deposit	2/169.0	4.0	29.0	24.0	20.9	10.3	11.5	100.0
The Engebøfjellet deposit	4/129.9	4.0	12.0	9.0	14.0	9.5	51.3	100.0
The Engebøfjellet deposit	5/61.9	7.0	34.0	21.0	20.6	13.6	3.3	100.0
Fimlandsgrend	K253B.94	1.0	11.0	7.0	7.4	10.1	63.0	100.0
Furefjellet	K308.94	7.0	34.0	21.0	18.1	14.7	4.5	100.0
Heianova	K251.94	2.0	15.0	19.0	19.2	12.8	32.8	100.0
Kleppstølen	K246.94	3.0	57.0	29.0	7.2	4.4	0.0	100.0
Kleppstølen	K252.94	3.0	57.0	30.0	5.9	3.7	0.0	100.0
Naustdal eclogite	K150.99	5.0	22.0	20.0	14.4	6.9	31.5	100.0
Naustdal eclogite	K255.94	10.0	52.0	27.0	8.9	1.3	0.0	100.0
Naustdal eclogite	K255-1.94	3.0	47.0	32.0	12.9	3.9	1.4	100.0
The Steinkorsen deposit	K143.99	21.0	74.0	5.0	0.0	0.0	0.0	100.0
The Steinkorsen deposit	K145.99	7.0	36.0	30.0	15.2	7.0	4.8	100.0
The Steinkorsen deposit	K146.99	7.0	42.0	30.0	16.1	1.8	2.9	100.0
The Steinkorsen deposit	K147.99	5.0	32.0	26.0	15.8	6.3	14.9	100.0
The Steinkorsen deposit	K148.99	2.0	14.0	19.0	12.5	11.3	40.8	100.0
The Steinkorsen deposit	K149.99	3.0	33.0	30.0	20.2	8.5	4.5	100.0
Average Førdefjord region:		5.7	36.6	23.0	13.5	7.5	13.5	100.0
Average for the Engebøfjellet deposit:		6.5	35.3	22.3	15.0	8.3	12.2	100.0
Average for the Steinkorsen deposit:		7.5	38.5	23.3	13.3	5.8	11.3	100.0

9. RUTILE MINERAL CHEMISTRY

XRF- and INA-analyses of rutile separates show large compositional variations with deposit type (Fig. 38). The CaO-content is critical since the upper limit in rutile feedstock by the titanium pigment production is normally 0.2 % CaO. Most of the rutile separates analysed have more than this amount of CaO. In practice a sufficient quality rutile concentrate can probably be made from many of the deposits, but that will be at the expense of recovery. In the case of the Engebøfjellet eclogite deposit, which is one of the few eclogites in Norway that has experienced beneficiation tests, a sufficiently low CaO-number is reached by a combination of gravity and magnetic separation methods with a recovery of approx. 50% (R. McLimans, DuPont, pers. comm.). Among the rutile separates analysed by NGU (Fig. 38) those from Engebøfjellet have the lowest CaO-values of the eclogite deposits.

Rutile separates from rutile-bearing albitites and scapolite rocks in the Bamble province do also have high CaO-values; it is therefore probable that CaO would be a major problem in the beneficiation of these ores as well, although this has not been tested. For some of the other rutile-bearing Bamble rocks the CaO in the rutile separates is low, indicating that this element would be a lesser problem in case of mining from these deposits.

The three bar-graphs labelled (3), (4) and (5) in Fig. 38 illustrates the significant variation in CaO, U & W, and Cr & V, respectively, in the rutile separates from the various deposit types. The striking difference in U and W (graph labelled 4) for rutile from eclogite deposits compared to rutile from the other deposit types, reflects that U and W was not available during the eclogitisation process under which the rutile formed, while in the Bamble deposits these elements must have been available in significant amounts. For elements such as Cr and V the difference between the various ore deposit types is not very distinct, except that rutile from albitites (Lindvikkollen) and scapolitised gabbros (Ødegården) are particularly enriched in vanadium.

10. RUTILE-FORMING HYDROTHERMAL SYSTEMS

Fluids play a major role in the formation of eclogite rutile deposits as well as the metasomatic rutile deposits. Eclogites are formed by high-pressure metamorphism in which the eclogitisation process, i.e. the metamorphic transformation of an amphibolite- or granulite facies mineral assemblages into an eclogite mineral assemblage with omphacite and garnet as the main silicate minerals and with rutile as the stable oxide mineral, is triggered by the influx of fluids along fracture zones. This has been well described for eclogites in the Bergen region by Austrheim & Griffin (1988), Austrheim (1987, 1990). See also Svensen et al. (1999) for further details of the composition of eclogite-facies fluids. However, the amounts of fluids present in the eclogitisation process are probably small compared to the extensive fluid infiltration involved in the formation of the metasomatic rutile deposits.

The changes in major- and trace element composition associated with the eclogitisation process is negligible, while in the formation of the metasomatic rutile deposits the fluids leads to not only new mineral assemblages but also to an entirely different chemical composition of the rock. The rutile-bearing scapolite-hornblende rock (called ødegårdite by Brøgger 1934) at Ødegården in the Bamble region is an example of a rutile deposits formed by this kind of process.

Hydrothermal/metasomatic alteration of ilmenite-bearing rocks in which ilmenite is decomposed and iron is transported away by the hydrothermal fluids while titanium remains to form rutile, is probably a process that has been active in various geological terrains. Scapolitisation and albitisation are common features in several geological provinces in Southern Scandinavia, as pointed out in the following section.

11. MINERAL DEPOSITS ASSOCIATED WITH MESO-PROTEROZOIC NA-METASOMATISM IN SOUTHERN SCANDINAVIA

By Peter Ihlen (NGU)

This section is based on the idea that a variety of hydrothermal mineral deposits in southern Scandinavia including base metal and gold deposits, have a genetic relationship to major hydrothermal systems associated with the formation of rutile deposits at depth.

The Proterozoic complexes in southern Scandinavia are characterised by widely distributed areas containing multiple hydrothermal centres with structurally controlled and polystage Na-metasomatism. The individual centres which comprises massive albitites and variably albitised orthogneisses, supracrustals and intrusives, frequently reach dimensions exceeding 1km². In addition, the Proterozoic complexes outside these large-scale metasomatic systems are punctured by scattered breccia pipes composed of albitised fragments in a matrix of chlorite, apatite, calcite, albite and/or sulphides. Most of the metasomatic rocks and breccias are assumed to have formed during the Gothian (1.5-1.7 Ga) and Sveconorwegian (0.9-1.1 Ga), though details regarding their development and geochronology are in most cases missing. The metasomatic systems which also contain other genetically related types of alteration and veins as well as ore mineralisation, were in the past exploited for Fe, rutile, Cu, Au, apatite, dimension stones (magnesitic serpentinites), and presently for dolomite, calcite and aggregate. Some of the systems have also been prospected for uranium. The most prominent areas affected by albite alteration in southern Scandinavia are summarised below, in order from east to west.

Loftahammar, Sweden

Na-metasomatism occurs widespread along the northeastern margin of the Vimmerby batholith (Småland granitoids) of the Trans-Scandinavian Igneous Belt (TIB). Albitisation is located at the contact zones between the Västervik meta-arenites (1.9-2.0 Ga) and the Vimmerby (1.80 Ga) and Loftahammar (1.84 Ga) granitoids. All of these units have been affected by fracture-bound albitisation which defines a 30km wide zone along the southwestern margin of the Loftahammar-Linköping Deformation Zone (LLDZ), to which it is assumed genetically related. The LLDZ represents a WNW-ESE striking, dextral, transpressional, brittle-ductile shear zone which is believed to have developed mainly in the period 1.80-1.74 Ga, though yielding Ar/Ar ages as low as 1.5 Ga. Some of the albitites show late replacement by scapolite. In the albitised areas only subordinate mineral deposits occur,

including albitite-hosted quartz veins enriched in coarse-grained Nb-rutile and shear-hosted Cu-Co-Au veins (e.g. Gladhammar deposit) formed subsequent to the main shearing event.

Dalsland, Sweden

Albitisation spatially related to the unconformity between the metasedimentary rocks of the Dal Fm. (c. 1.05 Ga) and underlying protomylonitic Åmål granitoids (c.1.6 Ga). Exploration work has revealed numerous radiometric anomalies both in the basement and in the basal part of the cover sequence. The basement anomalies occur in areas where the mylo-gneisses carry enhanced concentrations of hematite along the shear foliation. Uraninite occurrences recognised in the basal part of the Dal Fm. are mainly confined to albitites replacing greenschist facies mica schists, which occur below para-autochthonous units of basement gneisses. In the mineralised areas the underlying basal quartzites of the Dal Fm. are strongly silicified along bedding-parallel quartz breccias. At Åsnebo deposit the uranium-bearing albitites are intersected by quartz veins carrying Fe-oxides, uraninite, Cu-sulphides and native gold.

Mylonite Zone, SE Norway and SW Sweden

Na-metasomatism representing an intra-shearing hydrothermal event, is related to the waning stage of early semi-brittle, dextral shearing along the Mylonite Zone which occurs along the boundary between variably deformed TIB granitoids in the north (1.65-1.74 Ga) and migmatitic Åmål granitoids (c. 1.60 Ga) in the south. Hematite ores locally overprinted by Cu-sulphides and fluorite, occur as dissemination, crackle breccias, stockwork and intergranular replacement in albitites and partly albitised para- and orthogneisses as well as in quartz veins. More than 60 separate Fe-oxide ore bodies, some exceeding 0.5 Mt, were worked in the past. The albitisation is controlled both by transverse and shear-parallel structures developed in TIB granitoids including proto-mylonitic tonalites (c. 1.74 Ga) and gneissic to massive granites (1.65-1.70 Ga), as well as volcanosedimentary rocks of the Kongsvinger Gp. of uncertain age. The Na-metasomatism seems to have formed under upper greenschist facies conditions. A younger uplift-related and post-shearing hydrothermal event defined by the Eidsvoll gold lodes, comprise auriferous sulphide-quartz veins enveloped by pyrite-sericite alteration and locally by albitisation. These veins formed at c. 0.8-0.9 Ga and under more low-grade conditions than the albitites.

Bamble-Modum sector, Norway (See also Chapter 4)

The Bamble-Kongsberg-Modum sector includes rocks affected both by Kongsbergian/Gothian (c. 1.58 Ga) and Sveconorwegian (c. 1.1 Ga), medium- to high-grade, tectonothermal events. During the waning stage of the Sveconorwegian orogeny, the sector became uplifted as a consequence of north-northwest directed transpression along the Kristiansand-Bagn Shear Zone. Several types of albitic rocks are encountered in the Bamble-Modum sector where they mainly occur inside or immediately adjacent to deformed gabbroic bodies intruding meta-arenitic sequences. These are characterised by sillimanite quartzites and schists with detrital zircons yielding minimum ages of c. 1.47 Ga, i.e. deposited subsequent to the Gothian orogeny.

Two major episodes of albitisation which formed under amphibolite to greenschist facies conditions, can be recognised. The early episode, pre-dating late folding and shearing, is characterised by the formation of large bodies of fine- to medium-grained albitites which occur commonly inside the amphibolitic margins of meta-gabbros as in the Kragerø and Grimstad area of the Bamble sector. The albitites which frequently contain nebulitic remnants of the amphibolitic protoliths, can be separated into a number of sub-types according to their contents of subordinate constituents such as quartz, rutile (kragerøite), diopside, calcite, actinolite, hornblende, gedrite-antophyllite, titanite, garnet, tourmaline and apatite. Some of the albitites carry locally high concentrations of rutile and hematite which were mined in the past. Titanites from a first generation albitite in the Modum sector yield an U/Pb age of 1.08 Ga.

The second episode of Na-metasomatism is related to a period of mainly brittle deformation and fracture-bound hydrothermal activity starting with the transformation of meta-gabbros and

amphibolites to rocks composed dominantly of hornblende and scapolite, informally termed ødegårdites. The ødegårdites and adjacent paragneisses is frequently intersected by multiple generations of veins composed of variable proportions of scapolite, hornblende, apatite, rutile, talc, phlogopite, enstatite, carbonates, quartz, Fe-sulphides, Fe-oxides and/or albite. The early generation of veins, often carrying Fe-sulphides (pyrrhotite), are characterised by enrichment apatite as in the apatite-enstatite-phlogopite veins at Ødegården apatite mine in Bamble. The scapolite and apatite veins are succeeded by albite veins and albite-bearing breccias, frequently with associated albitisation of wall-rocks and breccia fragments. These veins and breccias may grade into types being filled dominantly by Fe-oxides and subordinate Cu-sulphides (Langøya mines, Kragerø), as well as quartz, dolomite and calcite. Dolomite veins at Kragerø and calcite breccias at Modum are presently mined.

Telemark-Setesdal region, Norway

Albitisation occurs only subordinately in the Telemark-Setesdal region where it is developed locally in association with Au-Cu and Cu veins and breccias of Sveconorwegian age. However, in a number of places Na-metasomatism, in the form of scapolitised gabbros, are encountered as in the Nissedal outlier. The outlier being composed of mixed volcanosedimentary rocks of the Telemark Supergroup (1.05-1.50 Ga), contain areas with ødegårdites and spatially associated magnetite-apatite deposits. These deposits range from small veins and breccia bodies to larger stratabound horizons which were mined at Søftestad. The Søftestad deposit has by previous workers being classified as a Kiruna-type deposit. These deposits are in many aspects comparable to the Lyngrot deposits in the Bamble sector. The common presence of apatite veins in areas with Na-metasomatism may indicate that the Fe-P ores developed in conjunction with comparable hydrothermal processes.

The Egersund province, Norway (see also Chapter 4)

The Egersund province which comprises massif type anorthosites and associated noritic intrusives where emplaced into the high-grade rocks of the Agder gneiss complex at c. 0.93 Ga. The anorthosites of the Åna-Sira massifs show widespread signs of bleaching and albitisation along faults and fractures. This fracture-bound alteration has often coalesced into irregularly shaped areas with pervasive transformation of the anorthosites into light grey rocks composed dominantly of albite and variable amounts of epidote, actinolite and salite (cpx). The altered rocks which are exploited as white aggregate, may reach surface dimensions of several square kilometres. Their formation is probably related to post-orogenic cooling and unroofing of the anorthosite complex which occurred according to Rb/Sr biotite-whole-rock ages, in the period 0.90-0.85 Ga.

Regional features

Conceptual models for the formation of these large scale systems of Na-metasomatism have to take into consideration the following main features:

- Widespread occurrences within the Sveconorwegian terrains where the metasomatism occurs superimposed on low- to high-grade rocks
- The metasomatism are related to brittle deformation structures and breccia pipes developed both prior to and subsequent to late Sveconorwegian shearing and folding.
- The metasomatism occurs frequently in conjunction with post-Gothian, arenitic cover sequences situated along regional shear belts.
- The mineral assemblages indicate interaction with fluids becoming progressively more oxidised and leading to late deposition of hematite-rich ores in combination with uraninite, Cu-sulphides and/or native gold.
- The position of possibly related Kiruna-type magnetite-apatite ores in the evolution of the Na-metasomatism is presently unknown.

In summary: It is probable that large-scale, deep-seated hydrothermal systems causes extensive leaching of a number of elements such as Fe, Cu, Zn, etc.; in this process ilmenite

breaks down, iron is transported away by hydrothermal fluids, and titanium remains in rutile. Such processes can produce significant volumes of rutile-enriched rocks, as demonstrated at the Ødegård deposit in the Bamble region. The large amounts of metals that are leached by the metasomatic process are precipitated elsewhere in the crust due to changes in the physical and chemical environment, leading to the formation of a number of epigenetic ore deposit types. Ore deposits that might fit into this generalised model can be found in several areas of southern Scandinavia. Further research is needed to verify the model and point out the most favourable areas for rutile deposits as well as for hydrothermal metal deposits.

12. THE RUTILE DATABASE

Some information generated by the project is stored in a PC database (Microsoft Access). The design of the database can be changed if needed. Standard report routines summarising specific type of information.

The database contains a series of linked tables:

- 1-*REGIONS* giving general information of the regions.
- 2-*AREAS* giving general information of the areas.
- 3-*LOCALITY* giving specific information of the localities.
- 4-*SAMPLES* giving specific information of the samples.
- The *ANALYSES* table contain major element analyses from rutile deposits.
- The *GRAIN SIZE INTERV* table gives image processing data used for plotting the histogram graphs.
- The *MAPLOT* table is used for plotting localities in ArcView maps.
- The *OXIDE GRAIN DATA* table contains the image processing data used for plotting the cumulative grain-size distribution graphs.

13. DISCUSSION AND CONCLUSION

Deposit types The two main types, rutile-bearing eclogite deposits in Western Norway and various metasomatic rutile deposits in the Bamble region of Southernmost Norway, were formed by very different geological processes. The eclogites formed as a consequence of high-pressure Caledonian metamorphism at approx. 400 Ma; during the eclogitisation process iron from ilmenite entered garnet while titanium remained to form rutile. The whole-rock chemistry of the rock were practically unaffected by this process.

In contrast, the metasomatic deposits in the Bamble region were formed by Proterozoic (probably approx. 1150 Ma) hydrothermal processes at amphibolite-facies metamorphic conditions. In this process ilmenite decomposed under the influence of the fluids; iron was carried away in the hydrothermal system, while titanium remained to form rutile. From a general ore-genetic point of view such metasomatic processes are particularly interesting since they provide a mechanism for leaching large amounts of metals from source-rocks at a deep level in the crust, to be transported upwards along major structures/shear-zones, and

precipitated and concentrated into a variety of hydrothermal ore deposits. According to this model, which needs to be further investigated and verified, the formation of metasomatic rutile deposits is closely connected with the formation of various shear-zone related ore deposits and Na-metasomatism.

To our knowledge, the first who pointed out such relationships was Brøgger (1934). He suggested that a genetical relationship existed between the brecca-related iron ores at Langøy (southeast of the town of Kragerø) and the Ødegård rutile-bearing scapolite-hornblende rock a few kilometres north-east of Langøy; in such a way that the metasomatism that made the Ødegård deposit provided the iron for the Langøy iron ores.

TiO₂-rich source-rocks Since rutile deposits form by the transformation of ilmenite-bearing rocks to rutile-bearing rocks by either metasomatism or eclogitisation, the formation of a significant rutile deposit is dependant of a large, titanium-rich protolith. Potential protoliths with 2-3 % TiO₂ are common, consequently most rutile deposits have rutile grades in this range. Rutile deposits of economic interest with 3-5 % rutile, such as some eclogites in the Førdefjord and Dalsfjord regions and some of the metasomatic deposits in the Bamble region, are believed to have formed by the conversion from relatively titanium-enriched, ilmenite-bearing gabbroic protoliths. In theory, even more titanium-rich rocks, such as disseminated to massive ilmenite-titanomagnetite ores, can under ideal conditions be transformed to rutile-bearing rocks with the same titanium content. A few rutile-rich mineralisations in the Bamble, Bergen and Dalsfjord regions might represent such deposits, although these are far too small to be of any economic interest.

The overview maps showing the combined distribution of ilmenite/titanomagnetite deposits and rutile occurrences in Norway (Fig. 1 and Appendix 1), give a geographic indication of suitable areas for rutile exploration. Favourable areas are defined by the combined presence of (1) ilmenite/titanomagnetite deposits, which are the product of effective magmatic Fe-Ti enrichment processes, and (2) rutile occurrences, which indicates that effective ilmenite to rutile transformation processes have been active in some parts of the region, but not everywhere. Such areas might contain undiscovered, large rutile-rich (> 5% rutile) deposits. All the major Fe-Ti provinces in Norway contain ilmenite/titanomagnetite deposits which are sufficiently large and Ti-rich to be of economic interest if most of the titanium had been in rutile. Therefore, the Fe-Ti provinces within the West Norway eclogite province (from Bergen and northwards) are all of potential interest for rutile in eclogites, while the Bamble province is of interest for metasomatic rutile deposits. Rutile-forming processes have also been active in the Rogaland anorthosite province, but good indications of significant volumes of rutile-bearing rocks have not been found in that region.

However, no ilmenite/titanomagnetite deposits are known in the Førdefjord eclogite region, although this region contain the most significant rutile deposits discovered so far in Norway, with rutile grades of 3-5 % over very large volumes and up to 6-7 % locally. One explanation might be that since the eclogitisation process in the Førdefjord region have been complete, at least on the northern side of Førdefjord where the most Ti-rich eclogites are found, massive to semi-massive magmatic ilmenite/titanomagnetite enrichments were decomposed during the eclogitisation process and replaces by rutile- and garnet-rich eclogite.

In the neighbouring Dalsfjord eclogite region, just south of Førdefjord, the eclogitisation has not been complete in all parts of the region; this region contain a number of Proterozoic massive to disseminated ilmenite/titanomagnetite deposits and occurrences associated with incompletely eclogitized gabbroic rocks.

It is also, however, possible that the Førdefjord region have not contained any massive to semi-massive ilmenite/titanomagnetite deposits such as those found in the Dalsfjord region.

The Førdefjord example shows that focusing the continued rutile exploration based on the combined ilmenite/titanomagnetite – rutile occurrence argument, such as presented above, is no more than a helpful tool in sorting out favourable areas; there might still be new areas yet to be identified, that might be highly attractive for rutile.

The anorthosite connection The occurrences of eclogite rutile deposits are associated with large volumes of anorthosites in the Bergen region (Figs. 5 and 6), where eclogites have been formed by the eclogitisation of anorthosites as well as a variety of associated mafic and intermediate rocks, some of which are Ti-rich. Significant volumes of anorthosites do also occur in the Dalsfjord region (south of Saudal; Fig. 7) where they are a part of a gabbroic intrusion. Massive to disseminated ilmenite – titanomagnetite ores occur within this intrusion. Some eclogites, such as the Saudal eclogite, are eclogitized fragments of the intrusion.

Minor anorthosites have been found in the Førdefjord region, although any relation between these anorthosites and the Ti-rich eclogites have not been found.

Large volumes of anorthosites occur in the Nordfjord region, but no associated Ti-rich rocks have been identified.

The presence of anorthosites is an indication that significant crystal fractionation processes have been active in the associated magma, which *might* have given distinct enrichment of titanium somewhere in the magmatic sequence. This is certainly the case in the Rogaland anorthosite province, in the Bergen region as well as in the Dalsfjord region. In the Førdefjord region the connection is unclear (but possible), and in the Nordfjord region no Ti-rich rocks have been found.

Rutile mineral chemistry: A distinct difference between rutile from eclogite deposits and rutile from the metasomatic deposits, is that rutile from eclogites contains less amounts of trace elements, particularly uranium. This has to do with different availability of uranium and other elements in the fluid regimes involved in the formation of the respective ore types. In the case of uranium, the element was probably not present in the fluids involved in the eclogitisation process, while it must have been abundant in the fluids that were active during the formation of the metasomatic rutile deposits.

The ***CaO***-content in rutile separates is caused by impurities of calcium-bearing silicate minerals in the separates, and is closely connected to the mineralogical characteristics of the respective deposits, in which Ca is a major element of most silicates. Of particular importance is the alteration of rutile to titanite associated with retrogressive metamorphism, i.e. secondary alteration of the host-rock. The degree of retrogression, which significantly affects the mineralogical qualities of the ore, and then also the amounts of CaO that end up in rutile separates, varies largely from deposit to deposit.

The rutile *grain-size* varies considerably between deposit type as well as between regions. Grain-size variations can also be distinct within the individual deposits. The most fine-grained rutile is found in deposits in the Førdefjord area such as Engebøfjellet and Steinkorsen.

The reason for the rutile grain-size variation is complex and poorly understood. One important factor is the titanium oxide grain-size in the protolith; larger grain-size in the protolith will in many cases be reflected in a large rutile grain-size in the eclogite or the metasomatic deposit. In the case of gabbroic or anorthosite protoliths the titanium oxide grain-size will usually be more than sufficient.

Another important factor is the metamorphic or metasomatic conditions. Static eclogitisation tend to preserve the oxide grain-size reasonably well while eclogite-facies deformation break up the larger grains into fragments. This is certainly the case for the Førdefjord eclogites which are intensively deformed under eclogite-facies conditions, consequently the rutile is fine-grained.

The overall *P-T evolution* path is probably less important for the rutile grain-size, but is important for the retrograde alteration of rutile to ilmenite or titanite; the faster the uplift and the less uplift-related deformation, the better. These circumstances need to be further investigated.

Favourable areas for further investigations: Based on the present information the Engebøfjellet – Steinkorsen – Naustdal area on the northern side of Førdefjord is the most favourable for large volumes of rutile ore. The documented resource at the Engebøfjell rutile/eclogite deposit is 400 Mt with approx. 4 % rutile, based on investigations by DuPont/Conoco/NGU in 1995-97. The Naustdal village eclogite deposit is roughly similar to Engebøfjellet in outcrop and mineralogical characteristics, but has avoided significant investigations due to the nearness of the Naustdal village. The Steinkorsen eclogite and gravity anomaly between Engebøfjellet and the Naustdal eclogite, might also represent a resource similar to Engebøfjellet. All-in-all the rutile ore resource potential in these areas on the northern side of Førdefjord might be roughly 1000 Mt with 3-5 % rutile.

Table 7: Advantages and disadvantages when considering the mining possibilities in the Førdefjord region.

Advantages	Disadvantages
Nearness to a deep fjord that will provide good shipping facilities as well as waste deposit possibilities at the bottom of the fjord at 350-400 m depth.	The rutile grades are relatively low for a hard-rock rutile deposit, which is also the case for other rutile deposits in Norway.
The infrastructure in the Førdefjord region is reasonably good.	A small rutile grain-size leads to a relatively low rutile recovery.
The rutile resource potential is the largest known in Norway. Ideally, a well-situated beneficiation plant with good shipping and waste-deposit facilities, can have a resource base of several large ore-deposits in the surroundings.	Mineralogical variations related to various degree of retrograde alteration might lead to problematic variations in beneficiation characteristics and rutile recovery.
	There are no mining traditions in the region

Table 8: Norway's major rutile deposits

Deposit	Region	Type ³	Cate- gory ⁴	% TiO ₂	Rutile /TiO ₂	Grain- size ¹	Tonn- age ²	Proximity to the sea
Engebøfjellet	Førdefj.	E	1	3-5	> 0.9	100	> 400 Mt	0 km
Steinkorsen	Førdefj.	E	1	3-5 (?)	> 0.9 (?)	100	L	3 km
Naustdal	Førdefj.	E	1	3-5 (?)	> 0.9 (?)	100	L	1 km
Fureviknipa	Førdefj.	E	2	3-5	0.6	100	S	2 km
Saurdal	Dalsfj.	E	2	3-6	0.4	200	L	1 km
Orkheia	Dalsfj.	E	2	2-4	> 0.9	200	S	2 km
Ramsgrønova	Dalsfj.	E	2	2-4	> 0.9	250	S	5 km
Husebø	Bergen	E	2	2-5	0.6	200	S	0 km
Vassbotn	Ålesund	E	2	2-3	0.5	150	S	3 km
Ødegård	Bamble	M	1	2-4	> 0.9	250	S	3 km
Lindvikkollen	Bamble	M	2	2-4	> 0.9	250	S	0 km

¹ Estimated average oxide grain-size (microns). ² Tonnage number is based on drilling (Engebøfjellet). Other alternatives are L (large, probably > 100 Mt ore), S (significant, probably < 100 Mt). ³ E (eclogite), M (metasomatic). ⁴ Deposit category term used in Appendix 1: Major deposit (1), Significant deposit (2)

Some advantages and disadvantages of the Engebøfjellet – Steinkorsen – Naustdal area when considering mining possibilities, are indicated in Table 6, while Table 7 summarises some key information for a selection of deposits. Engebøfjellet is the only deposit where a large tonnage has been actually documented by drilling. Eclogite deposits such as Fureviknipa, Saurdal, Orkheia, Ramsgrønova and Husebø and the Ødegården metasomatic deposit (in Bamble), have been relatively detailed sampled on the surface. In the case of Saurdal, Orkheia and Ødegård reconnaissance core drilling were carried out in the early 90's; these core are available at NGUs core storage facility. The Lindvikkollen rutile/albitite deposit was drilled by the company A/S Sydvaranger around 1973; these cores are now in the property of the company A/S Prospektering, and are not available at NGUs core storage.

Other areas with a significant ore resource potential are the Dalsfjord eclogite province and the Holsnøy area in the Bergen province. In both these areas, rutile is significantly more coarse-grained than in the Førdefjord eclogites. A disadvantage of the Holsnøy area is that the eclogites are more extensively retrograded with the alteration of rutile to ilmenite. Eclogites in the Dalsfjord area have particularly favourable mineralogical characteristics with a combined large grain-size and a high rutile/TiO₂-ratio. The Saurdal eclogite is an exception since it is significantly retrograded (it is cut by a E-W trending shear-zone) with much of the rutile altered to ilmenite.

In the case that rutile from the Førdefjord eclogites would be too fine-grained to be really attractive from a mining/beneficiation point of view, then the Dalsfjord province would probably be the best alternative in the further exploration for rutile in Norway.

However, based on the information available at present, continued investigations of rutile deposits in Norway should focus on the areas on the northern side of the Førdefjord, as pointed out in some more detail in Chapt. 2. Some rutile exploration could also be carried out in the Dalsfjord and Bergen eclogite provinces and of metasomatic rutile deposits in the Bamble province.

Further geological research should be done to study the effects of retrogression on the rutile ore quality, particularly related to the formation of titanite from rutile and ilmenite. Research should also be carried out on the significance of major hydrothermal systems in the

formation of metasomatic rutile deposits as well as of various types of hydrothermal ore deposits

14. REFERENCES

This reference list covers the eclogite province of W. Norway, the Bamble province and the Rogaland anorthosite province. Only some of these references are referred to in this report

- Agrinier, P., Javoy, M., Smith, D.C. and Pineau, F. 1985: Carbon and oxygen isotopes in eclogites, amphibolites, veins and marbles from the Western Gneiss Region, Norway. *Chem. Geol.* 52, 145-162.
- Andersen, T.B. and Jamtveit, B. 1990. Uplift of deep crust during orogenic extensional collapse: A model based on field studies in the Sogn-Sunnfjord region of Western Norway. *Tectonics* 9, 1097-1111.
- Andersen, T.B., Osmundsen, P.T. and Jolivet, L. 1994. Deep crustal fabrics and model for the extensional collapse of the southwest Norwegian Caledonides. *J. struct. geol.* 16, 1191-1203.
- Austrheim, H. & Griffin, W.L. 1985: Shear deformation and eclogite formation within granulite-facies anorthosites of the Bergen Arcs, Western Norway. *Chem. Geol.* 50, 267-281.
- Austrheim, H. 1987: Eclogitization of lower crustal granulites by fluid migration through shear zones. *Earth Planet. Sci. Lett.* 81, 221-232.
- Austrheim, H. 1990: Fluid induced processes in the lower crust as evidenced by Caledonian eclogitization of Precambrian granulites, Bergen Arcs, Western Norway. Dr.phil. theses, Mineralogisk-Geologisk Museum, Univ. Oslo.
- Austrheim, K. & Mørk, M.B.E. 1988: The lower continental crust of the Caledonian mountain chain: evidence from former deep crustal sections in western Norway. *N.G.U. Spec. Publ.* 3, 102-111.
- Bingen, B. & van Breemen, O., 1998a: Tectonic regimes and terrane boundaries in the high-grade Sveconorwegian belt of SW Norway, inferred from U-Pb zircon geochronology and geochemical signature of augen gneiss suites. *Journal of the Geological Society London*, 155, 143-154.
- Bingen, B. & van Breemen, O., 1998b: U-Pb monazite ages in amphibolite- to granulite-facies orthogneiss reflect hydrous mineral breakdown reactions: Sveconorwegian Province of SW Norway. *Contrib. Mineral. Petrol.*
- Bingen, B., 1989: Geochemistry of Sveconorwegian augen-gneisses from SW Norway at the amphibolite-granulite facies transition. *Norsk Geologisk Tidsskrift*, 69, 177 - 189.
- Bingen, B., Demaiffe, D. & van Breemen, O., in press.: The 616 Ma old Egersund basaltic dike swarm, SW Norway, and late Neoproterozoic opening of Iapetus ocean. In: Demaiffe, D., 1996: *Petrology and Geochemistry of magmatic suites of rocks in the continental and oceanic crusts. A volume dedicated to Professor Jean Michot.* Université Libre de Bruxelles. Royal Museum for Central Africa (Tervuren).
- Bingen, B., Demaiffe, D. & van Breemen, O., 1997: Age, geochemistry and Sr, Nd isotopic data of the Egersund dyke swarm, SW Norway; time of opening of Iapetus along the Baltica Margin. *Terra Nova* 9 Abstract Supplement 1, 166.
- Binns R.A. 1967: Barroisite-bearing eclogite from Nautsdal, Sogn og Fjordane, Norway. *J.Petrol.* 8, 349-379.
- Bjørnstad, B. 1987: Geologisk utvikling av proterozoiske gneiser i ytre Romsdal, Vest-Norge. Cand. Sci. Oppgave, Univ. Oslo. 131 pp

- Bolle, O., 1998. Mélanges magmatiques et tectonique gravitaire dans l'Apophyse de l'intrusion de Bjerkreim-Sokndal (Rogaland, Norvège): pétrologie, géochimie et fabrique magnétique. Unpublished Ph. D. thesis, University of Liège.
- Bollingberg, H.J. and Bryhni, I. 1972: Minor element zonation in an eclogite garnet. *Contrib. Min. Petrol.* 36, 113-122.
- Brastad, K. 1977: En geologisk undersøkelse av anorthositter og andre bergarter på grensen mellom Nordfjord og Sunnmøre. Hovedfagsoppgave. Univ. Oslo.
- Brastad, K. 1983: Petrology of eclogite rocks within the Bjørkedalen peridotite, Western Norway. *Bull.Min.* 106, 751-759.
- Brastad, K. 1985: Relations between anorthosites, eclogites and ultramafites in Bjørkedalen, Western Norway. In: *The Caledonide Orogen - Scandinavia and Related areas*. D.G. Gee and B.A. Sturt (eds). Wiley, Chichester, pp 859-872.
- Brueckner, H.K. 1969: Timing of ultramafic intrusions in the core zone of the Caledonides of southern Norway. *Am. J. Sci.* 267, 1195-1212.
- Brueckner, H.K. 1974: "Mantle" Rb/Sr and $87\text{Sr}/86\text{Sr}$ ratios for clinopyroxenes from Norwegian garnet peridotites and pyroxenites. *E.P.S.L.* 24, 26-32.
- Brueckner, H.K. 1977: A crustal origin for eclogites and a mantle origin for garnet peridotites: Strontium isotopic evidence from clinopyroxenes. *Contrib. Min. Petrol.* 60, 1-15.
- Brueckner, H.K. 1977: A structural, stratigraphic and petrologic study of anorthosites, eclogites and ultramafic rocks and their country rocks, Tafjord area, western south Norway. *N.G.U.* 332, 1-53.
- Bryhni, I. 1966. Reconnaissance studies of gneisses, Ultrabasites, eclogites and anorthosites in outer Nordfjord, Western Norway. *NGU*, 241, 1-68.
- Bryhni, I. and Andreasson, P.G. 1985: Metamorphism in the Scandinavian Caledonides. In: *The Caledonide Orogen - Scandinavia and Related areas*. D.G. Gee and B.A. Sturt (eds). Wiley, Chichester, pp 763-781.
- Bryhni, I. and Brastad, K. 1980: Caledonian regional metamorphism in Norway. *J. Geol. Soc. London* 137, 251-259.
- Bryhni, I. and Griffin, W.L. 1971: Zoning in eclogite garnets from Nordfjord, west Norway. *Contrib. Miner. Petrol.* 32, 112-125.
- Bryhni, I. and Grimstad 1970: Supracrustal and infracrustal rocks in the gneiss region of the Caledonides west of Breimsvatn. *N.G.U.* 266, 105-140.
- Bryhni, I. and Lutro, O. 1991. NAUSTDAL. Berggrunnsgeologisk kart 1218-3, foreløpig utgave, NGU.
- Bryhni, I., Bollingberg, H.J. and Graff, P.R. 1969: Eclogites in quartz feldspathic gneisses of Nordfjord, west Norway. *N.G.T.* 49, 193-225.
- Bryhni, I., Green, D.H., Heier, K.S. and Fyfe, W.S. 1970: On the occurrence of eclogite in western Norway. *Contrib. Miner. Petrol.* 26, 12-19.
- Bryhni, I., Krogh, E.J. and Griffin, W.L. 1977: Crustal derivation of Norwegian eclogites, a review. *Neues Jahrb. Miner. Abh.* 130, 49-68.
- Bryhni, I.: 1966: Reconnaissance studies of gneisses, ultrabasites, eclogites and anorthosites in outer Nordfjord, western Norway. *N.G.U.* 241, 1-68.
- Braathen, A. 1998: Polyphase brittle faulting in the Sunnfjord region, Western Norway: kinematic and timing. *NGU report no. 98.007*, 42 p.
- Buer, K.Y., 1982: Bruddtektoniske studier omkring gruvefeltene Dalen-Kjørholt (Brevik) og Titania (Tellnes). I: *Sammenheng sprekker/spenning i berg*. Hovedfagsoppgave, Universitet i Oslo.
- Buer, K.Y., 1985: Bruddtektoniske studier omkring gruvefeltene Dalen-Kjørholt (Brevik) og Titania (Tellnes). I: *Sammenheng sprekker/spenning i berg*. Bergverkenes Landssammenslutnings Industrigruppe, Teknisk Rapport nr. 60, 67-185.
- Bugge, A., 1963: Norges molybdenforekomster. *NGU nr.* 217.

- Carlson, A., 1945: Malmforekomster og Geologi i Sokndal-Egersundområdet. Upublisert rapport, 78 pp. Titania A/S.
- Carswell, D. A. 1990. Eclogite and eclogite facies: Definition and classification. In: *Eclogite Facies Rocks*, Blackie, Glasgow, 1-13.
- Carswell, D.A. 1968a: Possible primary upper mantle peridotite in Norwegian Basal Gneiss. *Lithos* 1, 322-355.
- Carswell, D.A. 1968b: Picritic magma - residual dunite relationships in garnet peridotite at Kalskaret near Tafjord, south Norway. *Contr. Miner. Petrol.* 19, 97-124.
- Carswell, D.A. 1973: Garnet pyroxenite lens within Ugelvik layered garnet peridotite. *Earth Planet. Sci. Lett.* 20, 347-352.
- Carswell, D.A. 1981: Clarification of the petrology and occurrence of garnet lherzolites, garnet websterites and eclogites in the vicinity of Rødhaugen, Almklovdalen, West Norway. *N.G.T.* 61, 249-260.
- Carswell, D.A. 1986: The metamorphic evolution of Mg-Cr type Norwegian garnet peridotites. *Lithos* 19, 279-297.
- Carswell, D.A. and Cuthbert, S.J. 1986: Eclogite facies metamorphism in the lower continental crust. In: *The nature of the lower continental crust*. J.B.
- Carswell, D.A. and Gibbs, F.G.F. 1980: The equilibration conditions and petrogenesis of European crustal garnet lherzolites. *Lithos* 13, 19-29.
- Carswell, D.A. and Harvey, M.A. 1985: The intrusive history and tectonometamorphic evolution of the Basal Gneiss Complex in the Moldefjord area, west Norway. In: *The Caledonide Orogen - Scandinavia and Related areas*. D.G. Gee and B.A. Sturt (eds). Wiley, Chichester, pp 843-857.
- Carswell, D.A., Curtis, C.D. and Kanaris-Sotiriou R. 1974: Vein metasomatism in peridotite at Kalskaret, near Tafjord, south Norway. *J. Petrol.* 15, 383-402.
- Carswell, D.A., Harvey M.A. and Al-Samman A. 1983: The petrogenesis of contrasting Fe-Ti and Mg-Cr garnet peridotite types in the high grade gneiss complex of western Norway. *Bull. Min.* 106, 727-750.
- Carswell, D.A., Krogh, E.J. and Griffin, W.L. 1985: Norwegian orthopyroxene eclogites: calculated equilibration conditions and petrogenetic implications. In: *The Caledonide Orogen - Scandinavia and Related areas*. D.G. Gee and B.A. Sturt (eds). Wiley, Chichester, pp 823-841.
- Chauvet, A. 1989: Etude petrostructurale du substratum des bassins devoniens de l'Ouest de la Norvege: les processus d'amincissement de la croute caledonienne epaissie. Thesis doctorat. Univ. Montpellier. 281 pp.
- Cho, M. and Ernst, W.G., 1991: An experimental determination of calcic amphibole solid solution along the join tremolite-tschermakite. *American Mineral.*, 76, 985-1001.
- Cordellier, F., Boudier, F. and Boullier, A.M. 1981: Structural study of the Almklovdalen peridotite massif, southern Norway. *Tectonophysics* 77, 257-281.
- Cuthbert, S.J. 1985: Petrology and tectonic setting of relatively low temperature eclogites and related rocks in the Dalsfjord area, Sunnfjord, West Norway. Unpubl. PhD Thesis, Univ. Sheffield.
- Cuthbert, S.J., 1985: Petrology and tectonic settings of relatively low-temperature eclogites and related rocks in the Dalsfjord area, Sunnfjord, West Norway. Unpubl. PhD thesis, Univ. of Sheffield.
- Cuthbert, S.J., Harvey, M.A. and Carswell, D.A. 1983: A tectonic model for the metamorphic evolution of the Basal Gneiss Complex, Western South Norway. *J. Metam. Geol.* 1, 63-90.
- Dahl, J.M., 1980: Gruver og skjerp i Rogaland. Stavanger turistforening, årbok 1980.
- Dalsegg, E., Elvebakk, H., Gellein, O. & Kihle, O. 1999: Gravity measurements in eclogite mapping, Naustdal, Sogn og Fjordane, 1999. NGU report no. 99.124, 30 p.
- Dawson, D.A., Carswell, J. Hall and K.H. Wedepohl (Eds.). *Geol. Soc. London Spe. Publ.* 24, 193-209.

- De Haas, G.J.L.M. 1992: Source, evolution, and age of coronitic gabbros from the Arendal-Nelaug area, Bamble, Southeast Norway. Doctoral thesis, Mineralogisch-Geologisch Instituut. Utrecht, Netherlands. 128 p.
- Demaiffe, D. & Michot, J., 1985: Isotope geochronology of the Proterozoic crustal segment of Southern Norway: A review. in: *The deep Proterozoic crust in the North Atlantic Provinces*. AC Tobi and JLR. Touret (eds.). D. Reidel, NATO ASI series, 158: 411-433.
- Demaiffe, D., 1996: Petrology and Geochemistry of magmatic suites of rocks in the continental and oceanic crusts. A volume dedicated to Professor Jean Michot. Université Libre de Bruxelles. Royal Museum for Central Africa (Tervuren).
- Demaiffe, D., Weis, D., Michot, J. and Duchesne, J.C., 1986: Isotopic constraints on the genesis of the Rogaland anorthositic suite (Southwest Norway). *Chem. Geol.*, 57: 167-179.
- Dewey, J.F., Ryan, P.D. and Andersen, T.B. 1993: Orogenic uplift and collapse, crustal thickness, fabrics and metamorphic phase changes: The role of eclogites. In: *Magmatic Processes and Plate Tectonics* (edited by Prichard, H.M., Alabaster, T., Harris, N.B.W. and Neary, C.R.). *Spec. Publ. geol. Soc. Lond.* 76, 325-343.
- Dietler, T.N, Koestler, A.G and Milnes, A.G. 1985: A preliminary structural profile through the Western Gneiss Complex, Sognefjord, southwestern Norway. *Norsk Geol. Tidsskr.* 65, 233-235.
- Doan, P.H., 1996: Upgraded slag (UGS): implications for TiO₂ feedstock supply. I: 12th Industrial Minerals International Congress. Chicago 1996. Industrial Minerals.
- Dolan, M.L., Hains, D.H. & Ash, D.R., 1991: High-Alumina Rocks in Ontario: Resources and Process Technology. Industrial Mineral Background Paper #10, Ministry of Northern Development and Mines, Ontario.
- Dormann, P., 1993: Titanium minerals, Market research of Norwegian deposits. Dr.Ing.-thesis, the Norwegian Institute of Technology, Department of Geology and Mineral Resources Engineering, Trondheim.
- Duchesne, J. C. & Maquil, R., 1987: The Egersund-Ogna massif. I: Maijer, C. & Padget, P., (eds.) *The geology of southernmost Norway – an excursion guide*. NGU, Special Publication No. 1.
- Duchesne, J. C. & Maquil, R., 1987: The Rogaland Intrusive massif: western part. I: Maijer, C. & Padget, P., (eds.) *The geology of southernmost Norway – an excursion guide*. NGU, Special Publication No. 1.
- Duchesne, J. C. & Michot, J., 1987: The Rogaland Intrusive massif: eastern part. I: Maijer, C. & Padget, P., (eds.) *The geology of southernmost Norway – an excursion guide*. NGU, Special Publication No. 1.
- Duchesne, J. C. & Tobi, A. C., 1987: : The Rogaland Intrusive massif: eastern part. I: Maijer, C. & Padget, P., (eds.) *The geology of southernmost Norway – an excursion guide*. NGU, Special Publication No. 1.
- Duchesne, J. C., 1987: The Bjerkreim-Sokndal massiv. I: Maijer, C. & Padget, P., (eds.) *The geology of southernmost Norway – an excursion guide*. NGU, Special Publication No. 1.
- Duchesne, J.-C. & Michot, J., 1987: The Rogaland intrusive masses: Introduction. in: *The geology of southernmost Norway*. C. Maijer and P. Padget (eds.). *Norges geologiske undersøkelse Spec. Pub.* 1: 48.
- Duchesne, J.-C. & Wilmart, E. 1997: Igneous charnockites and related rocks from the Bjerkreim-Sokndal layered intrusion (Southwest Norway); a jotunite (hypersthene monzodiorite)-derived A-type granitoid suite. *Journal of Petrology* 38, 337-369.
- Duchesne, J.-C., 1970: Microtextures of Fe-Ti oxide minerals in the South-Rogaland anorthositic complex (Norway). *Ann. Soc. Géol. Belgique*, 93: 527-544.
- Duchesne, J.-C., 1996: Liquid ilmenite or liquidus ilmenite: a comment on the nature of ilmenite vein deposits. I: Demaiffe, D. (red.): *Petrology and geochemistry of magmatic suites of rocks in the*

- continental and oceanic crusts. A volume dedicated to professor Jean Michot. Universite Libre de Bruxelles. Roal Museum for Central Africa (Tervuren). 73-82.
- Duchesne, J.-C., 1999: Fe-Ti deposits in Rogaland anorthosites (South Norway): geochemical characteristics and problems of interpretation. in: *Agricola Volume*, John Wiley.
- Duchesne, J.-C., 1999: Fe-Ti deposits in Rogaland anorthosites (South Norway): geochemical characteristics and problems of interpretation. in: *Mineralium Deposita* 34:182-198.
- Duchesne, J.-C., Denoiseux, B. & Hertogen J., 1987: The norite-mangerite relationships in the Bjerkreim-Sokndal layered lopolith (Southwest Norway). *Lithos*, 20: 1-17.
- Duchesne, J.-C., Maquil, R. & Demaiffe, D., 1985: The Rogaland anorthosites: Facts and speculations. in: *The deep Proterozoic crust in the North Atlantic Provinces*. A.C. Tobi and J.L.R. Touret (eds.), D. Reidel, NATO ASI series 158: 449-476.
- Duchesne, J.-C., 1972: Iron-titanium oxide minerals in the Bjerkreim-Sokndal Massif, south-western Norway. *J. Petrol.*, 13: 57-81.
- Dunn, S.R. and Medaris, L.G. Jr 1989: Retrograded eclogites in the Western Gneiss Region, Norway, and thermal evolution of a portion of the Scandinavian Caledonides. *Lithos* 22, 229-245.
- Ellis, D.J. and Green, D.H., 1979: An experimental study of the effect of Ca upon garnet-clinopyroxene Fe-Mg exchange equilibria. *Contrib. Mineral. Petrol.*, 71, 13-22.
- Elvebakk, H., Gellein, J. & Furuhaug, L. 1999: Gravity measurements in eclogite mapping, Naustdal, Sogn og Fjordane. NGU report no. 99.046, 52 p.
- Erambert, M. 1985: Etude petrologique de lentilles eclogitiques mafiques et ultramafiques et de leur encaissant a Essdalen, Vartdal, Sunnmøre Norvege. Thesis Univ Paris VI and Museum National d'Histoire Naturelle. 319 pp.
- Eskola, P. 1921: On the eclogites of Norway. *Skr. Norske Vidensk. Akad. Oslo, Mat.-Nat. Kl.I*, 8, 1-118
- Falkum, T., 1982: Geologisk kart over Norge - Berggrunnskart Mandal 1:250 000. NGU.
- Force, E.R., 1991: Geology of Titanium-Mineral Deposits. The Geological Society of America Special Paper 259.
- Foslie, G. 1980: En anvendt mineralogisk undersøkelse av rutilførende eklogitt ved Fureviknipa ved Førde i Sunnfjord. Unpubl. diplom-thesis, Tech. Univ. Norway, Trondheim, 94 p.
- Garmann, L.B., Brunfelt, A.O. and Heier, K. 1976: Scandium, chromium, iron, cobalt and nickel in some basic and ultrabasic rocks from west Norway. *Chem. Geol.* 18, 49-55.
- Garmann, L.B., Brunfelt, A.O., Finstad, K.G. and Heier K.S. 1975: Rare-earth element distribution in basic and ultrabasic rocks from west Norway. *Chem. Geol.* 15, 103-116.
- Gautneb, H., Wanvik, J.E. & Marker, M., 1998: Undersøkelse av to kvartsprøver fra Gjersdal, Lund kommune, Rogaland. NGU Rapport 98.109. Norges geologiske undersøkelse.
- Gebauer, D., Lappin, M.A., Grünenfelder, M. and Wyttenbach A. 1985: The age and origin of some Norwegian eclogites: a U-Pb zircon and REE study. *Chem. Geol.* 52, 227-247.
- Geis, H.P. (1967): Internal Elkem-report on vanadiferous magnetite deposits in Norway.
- Gierth, E. & Krause, H., 1973: Die ilmenitlagerstätte Tellnes (Süd-Norwegen). *Norsk geologisk tidsskrift*, 53: 359-402.
- Gilbert, M.C., Helz, R.T., Popp, R.K. and Spear, F.S., 1982: Experimental studies of amphibole stability. In: Veblen, D.R. and Ribbe, P.H. (Eds): *Amphiboles: Petrology and Experimental Phase Relations*. Min. Soc. America, Reviews in Mineralogy, Vol. 9B, pp 229-353.
- Gjelsvik, T. 1951: Oversikt over bergartene i Sunnmøre og tilgrensende deler av Nordfjord. N.G.U. 179.
- Gjelsvik, T. 1952: Metamorphosed dolerites in the gneiss area of Sunnmøre on the West coast of southern Norway. *N.G.T.* 30, 33-134.
- Gjelsvik, T. 1957: Geochemical and mineralogical investigations of titaniferous iron ores, west coast of Norway. *Econ. Geol.* 52, 482-498.

- Gjelsvik, T. 1960: The differentiation and metamorphism of the west Norwegian dolerites. Norsk Vidensk. Selsk. Skr. 3, 1-11.
- Gjelsvik, T., 1952: Metamorphosed dolerites in the gneiss area of Sunnmøre on the west coast of southern Norway. Nørsk Geologisk Tidsskrift, 30, 33-134.
- Godard, G., 1981: Lambeaux probables d'une croûte océanique subductée: les éclogites de Vendée (Massif Armoricain - France) . PhD thesis, Univ. of Nantes.
- Graham, C.M., Maresch, W.V., Welch, M.D. and Pawley, A.R., 1989: Experimental studies on amphiboles: a review with thermodynamic perspectives. Eur. J. Mineral., 1, 535-555.
- Green, D.H. and Ringwood, A.E., 1967: An experimental investigation of the gabbro to eclogite transformation and its petrological applications. Geochim. Cosmochim. Acta, 31, 767-833.
- Green, T.H. and Mysen, B. 1972: Genetic relationships between eclogite and hornblende + plagioclase pegmatite in Western Norway. Lithos 5, 147-167.
- Griffin, W. L. 1987. 'On the eclogites of Norway' -65 years later. Mineralog. Mag. 51, 333-343.
- Griffin, W.L. 1987: 'On the eclogites of Norway': 65 years later. Miner. Mag. 51, 333-343.
- Griffin, W.L. and Brueckner, H.K. 1980: Caledonian Sm-Nd ages and a crustal origin for Norwegian eclogites. Nature 285, 319-321.
- Griffin, W.L. and Brueckner, H.K. 1985: REE, Rb-Sr and Sm-Nd studies of Norwegian eclogites. Chem. Geol. 52, 249-271.
- Griffin, W.L. and Carswell, D.A. 1985: In situ metamorphism of Norwegian eclogites: an example. In: The Caledonide Orogen - Scandinavia and Related areas. D.G. Gee and B.A. Sturt Eds. Wiley, Chichester, pp 813-822.
- Griffin, W.L. and Mørk, M.B.E. 1981, Eds.: Eclogites and basal gneisses in Western Norway. Guide Excursion B1 Uppsala Caledonides Symposium. 88 pp.
- Griffin, W.L. and Qvale, H. 1985: Superferrian eclogites and the crustal origin of garnet peridotites, Almklovdalen, Norway. In: The Caledonide Orogen - Scandinavia and Related areas. D.G. Gee and B.A. Sturt Eds. Wiley, Chichester, pp 803-812.
- Griffin, W.L. and Råheim, A. 1973: Convergent metamorphism of eclogites and dolerites, Kristiansund area, Norway. Lithos 6, 21-40.
- Griffin, W.L., Austrheim, H., Brastad, K., Bryhni, I., Krill, A., Mørk, M.B.E., Qvale, H. and Tørudbakken, B. 1985: High pressure metamorphism in the Scandinavian Caledonides. In: The Caledonide Orogen - Scandinavia and Related areas. D.G. Gee and B.A. Sturt (eds). Wiley, Chichester, pp 783-801.
- Griffin, W.L., Austrheim, H., Brastad, K., Bryhni, I., Krill, A.G., Krogh, E.J., Mørk, M.B.E, Qvale, H. and Tørudbakken, B 1985: High-pressure metamorphism in the Scandinavian Caledonides. In The Caledonide Orogen; Scandinavia and related areas, vol. 2., 783-801.
- Grønlie, G., Mysen, B.O. & Bech, O.M. 1972: Gravity investigation of the Hareidlandet eclogite, western Norway. Nor. Geol. Tidsskr. 52, 305-311.
- Grønlie, G., Mysen, B.O. and Bech, O.M. 1972: Gravity investigation of the Hareidlandet eclogite, western Norway. N.G.T. 52, 305-311.
- Hagen, R., 1992: Titania - 90 år med ilmenitt. Geonytt 4, s. 12-14.
- Hamner, S., and Passchier, C., 1991. Shear-sense indicators: a review. Geol. Surv. Canada Paper 90-17, 72 p.
- Heldal, T. & Lund, B., 1994: Natursteinspotensialet i Rogaland anortosittkompleks. NGU-rapport 94.029. 73 sider.
- Heldal, T. & Lund, B., 1995: A regional study of the dimension-stone potential in labradorite-bearing anorthositic rocks in the Rogaland Igneous Complex. NGU bull. 427.
- Heldal, T., 1995: Undersøkelse av anortosittforekomster ved Hellevik, Rogaland, NGU Rapport nr. 95.055.

- Helz, R.T., 1973: Phase relations of basalts in their melting range at $P_{H_2O} = 5$ kbar as a function of oxygen fugacity. Part I : mafic phases. *J. Petrology*, 14, 249-302.
- Hernes, I. 1953: Eclogite-amphibolite on the Molde peninsula, southern Norway. *N.G.T.* 33, 163-184.
- Hernes, I. 1955: Geologisk oversikt over Molde-Kristiansunds området. *Kgl. Nor. Vitensk. Selsk. Skr.* 5, 17 pp.
- Holland, T.B.J., 1980: The reaction albite \rightleftharpoons jadeite + quartz determined experimentally in the range 600-1200 °C. *American Mineral.*, 65, 129-134.
- Hubaux, A., 1956: Different types de mineraux noirs de la région d'Egersund, Norvège. *Ann. Soc. Géol. Belg* 79: 203-215.
- Hubaux, A., 1960: Les gisements de fer titané de la région d'Egersund, Norvège. *Neues Jahrbuch für Mineralogie, Abhandlungen*, 94: 926-992.
- Jacobsen, V.W. 1977: Serpentinittisert olivinstein i Nordfjord. Hovedoppgave i Geologi, geol. Inst, Univ. Oslo. 185 pp.
- Jamtveit, B. 1984: High-P metamorphism and deformation of the Gurskebotn garnet peridotite, Sunnmøre, western Norway. *N.G.T.* 64, 97-110.
- Jamtveit, B. 1986: Magmatic and metamorphic history of the Eiksunddal eclogite complex, Sunnmøre, Western Norway. Thesis, Univ. Oslo. 158 pp.
- Jamtveit, B. 1987a: Metamorphic evolution of the Eiksunddal eclogite complex, western Norway, and some tectonic implications. *Contrib. Miner. Petrol.* 95, 82-99.
- Jamtveit, B. 1987b: Magmatic and metamorphic controls on chemical variations within the Eiksunddal eclogite complex, Sunnmøre, western Norway. *Lithos* 20, 369-389.
- Jamtveit, B., Bucher, K., & Austrheim, H. 1990: Fluid-controlled eclogitization of granulites in deep crustal shear zones, Bergen Arcs, Western Norway. *Contr. Miner. Petrol.* 104, 184-193.
- Jensen, J.C., Nielsen, F.M., Duschene, J.C., Demaiffe, D. & Wilson, J.R., 1993: Magma influx and mixing in the Bjerkreim-Sokndal layered intrusion, South Norway: evidence from the boundary between two megacyclic units at Storeknuten. *Lithos* 29: 311-325.
John Wiley and Sons. Chichester, United Kingdom.
- Jonsson, S., Feyling, C.E. & Jacobsen, A., 1987: Sokndal gjennom 150 år - med tilbakeblikk på tidligere tider. Sokndal kommune.
- Jonsson, S., 1982: Bergverksdrift i Sokndal. I: Ilmenitten, julenummer. *Titania A/S*.
- Karlsen, T.A., 1997: Geometry of fracture zones and their influence on the ore quality at the Tellnes ilmenite mine, Rogaland. NGU rapport no. 97.031. (NGU/Titania A/S).
- Karlsen, T.A., Nilsson, L.P., Marker, M., Gautneb, H. & Erichsen, E., 1998: Berggrunns-geologi og mineralske ressurser i Sokndals-området, Rogaland. Statusrapport. NGU-rapport 98.068.
- Karlsen, T.A., Schiellerup, H., McEnroe, S., Nilsson, L.P. & Korneliussen, A., 1996: Current research on ilmenite in the Egersund Province. NGU-rapport nr. 96.059. 40 s. (NGU/Titania A/S).
- Karpuz, M.R., 1993: Use of spot-XM satellite data for environmental and structural geological applications: Tellnes Mining Area, Rogaland District, Southwestern Norway. Collaborate Research Project Report (Structural Research Group Report No. 9). University of Bergen, Geological Institute, Geological Survey of Norway, Titania A/S.
- Kechid, S.A: 1984: Etude pétrologique et minéralogique des eclogites de Liset Stadtlandet - Norvege. Thesis Univ. Paris VI and Museum National d'Histoire Naturelle. 196 pp.
- Kildal, E.S. 1970: Geologisk kart over Norge, berggrunnskart Måløy, 1:250.000, norsk utgave. NGU.
- Kirkeby, T. 1988: En geologisk undersøkelse av gneiser og amfibolitter nord for Jølstravatnet i Sunnfjord, Sogn og Fjordane. Cand. Sci. Oppgave, Univ. Oslo.
- Knorn, H. & Krause, H., 1977: Die Verbandsverhältnisse südlich von Tellnes im Zentralteil des Åna-Sira-Massivs (Südnorwegen). *Norsk geologisk tidsskrift*, 57: 85-95.
- Knorn, H., 1975: Die Verbandsverhältnisse und ihre Beziehungen zu den Ilmenit-vererzungen im südlichen Zentralteil des Åna-Sira Massivs. Unpubl. PhD-thesis, T.U. Clausthal.

- Kolderup, C. F., 1897: Ekersund-Soggendalsfeltets bergarter og deres betingelser for anvendelse i steinindustrien. Bergens Museums Aarbog nr. 11.
- Kolderup, C.F., 1896: Die labradorfelse des westlichen Norwegens I: Das labradorfelsgebiet bei Ekersund und Soggendal. Bergen Mus. Årbok 1896, part V: 224 pp.
- Kolderup, N.H. 1960: Origin of Norwegian eclogites in gneisses. N.G.T. 40, 73-76.
- Korneliussen, A. & Foslie, G. 1985: Rutile-bearing eclogites in the Sunnfjord region, W. Norway. *Nor. geol. unders.* 402, 65-71.
- Korneliussen, A. & Furuhaug, L. 1991: Fureviknipa og Engebøfjellet rutilforekomster ved Førdefjorden, Sogn og Fjordane. NGU-report no. 91.171, 17 p.
- Korneliussen, A. & Robins, B., 1985: Titaniferous magnetite, ilmenite & rutile deposits in Norway. NGU bulletin 402.
- Korneliussen, A. 1979: Rutil i eklogitter fra Sunnfjord i Sogn og Fjordane. NGU rapport nr. 1717/1.
- Korneliussen, A. 1980: Jern og titanforekomster tilknyttet gabbroide, amfibolittiske og eklogittiske bergarter i Sunnfjord. Unpubl. NGU-report no. 1717/3, 40p.
- Korneliussen, A. 1980a: Tunge bergarter i Sunnfjord. NGU report no. 1717/2.
- Korneliussen, A. 1980b: Jern og titanforekomster tilknyttet gabbroide, amfibolittiske og eklogittiske bergarter i Sunnfjord. NGU report no. 1717/3, 40 s.
- Korneliussen, A. 1980c: Foreløpige resultater fra rutilundersøkelser ved Kvammen i Askvoll. NGU report no. 1717/4.
- Korneliussen, A. 1981: Rutil i eklogittiske bergarter i Sunnfjord, NGU report no. 1717/5, 27 p.
- Korneliussen, A. 1989: Rutil i eklogitt, Gulen, Sogn og Fjordane. NGU-report no. 89.110.
- Korneliussen, A. 1992: Rutile in eclogites, Western Norway. Report, DuPont/NGU collaboration project 1992. 21 p. + appendix.
- Korneliussen, A. 1994: Rutile-bearing eclogites in Western Norway. NGU report 94.013 to DuPont (confidential until 1 Jan. 1999), 152 p.
- Korneliussen, A. 1994: Rutile-bearing eclogites in Western Norway. NGU-report 94.013, 152 p.
- Korneliussen, A. 1996: Core-drilling at Engebøfjellet 1995-96; Dh1 to Dh5. NGU report 96.062 to DuPont (confidential until 1 May 2001), 155 p.
- Korneliussen, A. and Erambert, M. 1997: Core-drilling at the Engebøfjell rutile-bearing eclogite 1995/96; Dh1 to Dh10. NGU report 97.014 to DuPont (confidential until 31 Desember 2001), 141 p.
- Korneliussen, A. and Foslie., G. 1985: Rutile-bearing eclogites in the Sunnfjord region of Western Norway, *Nor. geol. Unders.* 402, 65-71.
- Korneliussen, A. and Furuhaug, L. 1991. Fureviknipa og Engebøfjellet rutilforekomster ved Førdefjorden, Sogn og Fjordane. NGU-report no. 91.171, 17 p.
- Korneliussen, A. and Furuhaug, L. 1993: Ødegården rutilforekomst: En rutilførende skapolittomvandlet gabbro ved Ødegårdens Verk, Bamble. NGU rapport 93.078, 46p.
- Korneliussen, A. Og Furuhaug, L. 1991: Fureviknipa og Engebøfjellet rutilforekomster ved Førdefjorden, Sogn og Fjordane. NGU-report 91.159, 28p.
- Korneliussen, A., Austrheim, H, Furuhaug, L., Lauritzen, T., Torbergsen, K 1991: Husebø rutilforekomst, Meland kommune, Hordaland. NGU-report no. 91.159, 28 p.
- Korneliussen, A., Austrheim, H., Furuhaug, L., Lauritzen, T., Rønning, J.S. & Røste, J. 1990: Rutilforekomster på Holsnøy, Meland kommune, Hordaland. NGU-report no. 90.008, 45 p.
- Korneliussen, A., Braathen, A., Erambert, M., Lutro, O. & Ragnhildstveit, J. 1998: The geology of the Engebøfjellet eclogite deposit and its regional setting. Confidential report to DuPont. NGU-report no. 98.081, 121 p.
- Korneliussen, A., Dormann, P., Erambert, M., Furuhaug, L. og Mathiesen, C.O. 1992: Rutilforekomster tilknyttet eklogittbergarter på Vestlandet og metasomatiske omvandlede bergarter og metasedimenter i Bamble-Arendal regionen. NGU-report no. 92.234. 43 p. + 45 p. appendix.

- Korneliussen, A., Erambert, M., McLimans, R.K. & Lloid, F. 1999: Ti/Fe-Ti oxides at different metamorphic stages in the Sunnfjord region, W. Norway: Implications for the genesis of rutile eclogite ore deposits. In Stanley et al. (eds) Mineral deposits: processes to processing. Proceedings of the fifth biennial SGA meeting and the tenth quadrennial IAGOD symposium, London 1999. Balkema, Rotterdam, 1105-1108.
- Krause, H. & Pape, H., 1975: Mikroskopische untersuchungen der mineralvergesellschaftung in erz und nebengestein der ilmenitlagerstätte Storgangen (Süd-Norwegen). Norsk geologisk tidsskrift, 55: 387-422.
- Krause, H. & Pedall, G., 1980: Fe-Ti-mineralizations in the Åna-Sira anorthosite, southern Norway. Geol. Surv. Finland Bull., 307: 56-83.
- Krause, H. & Zeino-Mahmalat, R., 1970: Untersuchungen an erz und nebengestein der grube Blåfjell in SW-Norwegen. Norsk geologisk tidsskrift, 50: 45-88.
- Krause, H., Gierth, E. & Schott, W., 1985: Ti-Fe deposits in the South Rogaland Igneous Complex, with special reference to the Åna-Sira anorthosite massif. In: Korneliussen, A. & Robins, B. (eds.): Titaniferous magnetite, ilmenite and rutile deposits in Norway. Norges geologiske undersøkelse Bull., 402: 25-37.
- Krill, A. 1980: Tectonics of N.E. Dovrefjell, Central Norway. PhD thesis, Univ. Yale.
- Krill, A. 1980: Tectonics of the Oppdal area - central Norway. Geol. Foren. Stockholm Forh. 102, 523-530.
- Krogh, E. and Carswell, D.A. 1995: HP and UHP eclogites and garnet peridotites in the Scandinavian Caledonides. In Coleman, R.G. and Wang, X. 1995: Ultrahigh pressure metamorphism, 244 - 298.
- Krogh, E.J. & Carswell, D.A. 1995: HP and UHP eclogites and garnet peridotites in the Scandinavian Caledonides. In Coleman, R.G. & Wang, X. Ultrahigh pressure metamorphism, Cambridge University press 1995, 244-298.
- Krogh, E.J. 1977: Evidence for a Precambrian continent-continent collision in western Norway. Nature 267, 17-19.
- Krogh, E.J. 1980a: Compatible P. T. conditions for eclogites and surrounding gneisses in the Kristiansund area, western Norway. Contrib.Min.Petrol. 75, 387-393.
- Krogh, E.J. 1980b: Geochemistry and petrology of glaucophane-bearing eclogites and associated rocks from Sunnfjord, western Norway. Lithos 13, 355-380.
- Krogh, E.J. 1982: Metamorphic evolution of Norwegian country-rock eclogites, as deduced from mineral inclusions and compositional zoning in garnets. Lithos 15, 305-321.
- Krogh, E.J. and Brunfelt A.O. 1981: REE, Cs, Rb, Sr and Ba in glaucophane-bearing eclogites and associated rocks, Sunnfjord, Western Norway. Chem. Geol. 33, 295-305.
- Krogh, E.J., 1980: Geochemistry and petrology of glaucophane-bearing eclogites and associated rocks from Sunnfjord, Western Norway. Lithos, 13, 355-380.
- Krogh, E.J., 1988: The garnet-clinopyroxene Fe-Mg geothermometer - a reinterpretation of existing experimental data. Contrib. Mineral. Petrol., 99, 44-48.
- Kullerud, K. & Bjørlykke, A., 1993: MgO-innhold i ilmenitt fra Tellnesforekomsten. Upublisert rapport til Titania A/S.
- Kullerud, K., 1996: MgO-innhold i ilmenitt fra Tellnesforekomsten - oppfølging av tidligere arbeider - avsluttende rapport. Institutt for Biologi og Geologi, Universitet i Tromsø, N-9037 Tromsø. Upublisert rapport til Titania A/S.
- Kullerud, K., Tørudbakken, B.O. and Ilebekk, S. 1986: A compilation of radiometric age determinations from the Western Gneiss region, South Norway. Nor. geol. Unders. 406, 17-42.
- Kullerud, L. & Machado, N. 1991: End of a controversy; U-Pb geochronological evidence for significant Grenvillian activity in the Bamble area, Norway. Terra Abstracts. 3, p. 504.
- Kullerud, L. 1987: Rb-Sr studie av gneiser i ytre Romsdal, Vest Norge. Cand. Sci. Oppgave, Univ. Oslo. 173 pp.

- Lappin, M.A. 1960: On the occurrence of kyanite in the eclogites of the Selje and Åheim districts, Nordfjord, SW Norway. N.G.T. 40, 289-296.
- Lappin, M.A. 1966: The field relationships of basic and ultrabasic masses in the basal gneiss complex of Stadlandet and Almklovdalen, S.W. Norway. N.G.T. 46, 439-495.
- Lappin, M.A. 1967: Structural and petrofabric studies of the dunites of Almklovdalen, Nordfjord, Norway. In P.J. Wyllie Ed. Ultramafic and related rocks. Wiley & Sons, New York. pp 183-190.
- Lappin, M.A. 1973: An unusual clinopyroxene with complex lamellar intergrowths from an eclogite in the Sunndal-Grubse ultramafic mass, Almklovdalen, Nordfjord, Norway. Min. Mag. 39, 313-320.
- Lappin, M.A. 1974: Eclogites from the Sunndal-Grubse ultramafic mass, Almklovdalen, Norway and the T - P history of the Almklovdalen mass. J.Petrol 15, 567-601.
- Lappin, M.A. and Smith, D.C. 1978: Mantle equilibrated orthopyroxene eclogite pods from the basal gneisses in the Selje district, western Norway. J.Petrol. 19, 530-584.
- Lappin, M.A. and Smith, D.C. 1981: Carbonate, silicate and fluid relationships in eclogite, Selje district and environs, S.W. Norway. Trans.Roy.Soc.Edinburgh, Earth Sci. 72, 171-193.
- Larsen, R., 1996: Distribution of Fe-Ti oxide minerals in the Ørslund, Bakka-Krune and Einebakka area of the Bjerkreim-Sokndal layered norite, Rogaland. NGU-rapport nr. 96.130. 9 s. (NGU/Titania A/S).
- Leake, B., 1978: Nomenclature of amphiboles. Mineral. Mag., 42, 533-563.
- Lindberg, 1985: Fe-Ti-P mineralizations in the Larvikite-Lardalite Complex, Oslo Rift. In: Korneliussen, A. & Robins, B. (red.): Titaniferous magnetite, ilmenite and rutile deposits in Norway. Norges geologiske undersøkelse Bulletin 402, 93-98.
- Maijer, C. & Padget, P., 1987: The geology of southernmost Norway - an excursion guide. NGU Special publication nr. 1.
- Maniar, P. D. and Piccoli, P. M. 1989. Tectonic discrimination of granitoids. Geol. Soc. Am. Bull. 101, 635-643.
- Matsui, Y., Banno, S. and Hernes, I. 1966: Distribution of some elements among minerals of Norwegian eclogites. N.G.T. 46, 364-368.
- Mauring, E. & Gellein, J., 1995: Gravimetriske målinger over Tellnes ilmenitt-forekomst, Sokndal kommune, Rogaland. NGU-r apport nr. 95.144.
- Mauring, E. 1996: Interpretation of a gravity profile a cross the Engebøfjellet rutile-bearing eclogite deposit. NGU report no. 96.061, 14 p.
- Mauring, E. and Gellein, J. 1996: Interpretation of a gravity profile across the Engebøfjell rutile-bearing eclogite deposit. NGU report no. 96.061.
- Mauring, E. and Gellein, J. 1997: Interpretation of gravity profiles at the Engebøfjell rutile-bearing eclogite deposit. NGU report no. 97.173, 29 p.
- Mauring, E., Gellein, J. and Korneliussen, A. 1997: Interpretation of two gravity profiles across the Engebøfjell rutile-bearing eclogite deposit. NGU report no. 97.002, 21 p.
- McEnroe, S., 1996: Rock-magnetic properties, oxide mineralogy, and mineral chemistry in relation to interpretation of the aeromagnetic map and the search for ilmenite reserves. NGU-rapport nr. 96.060. (NGU/Titania A/S).
- Mearns, E.W. 1986: Sm-Nd ages for Norwegian garnet peridotite. Lithos 19, 269-278.
- Medaris, L.G. Jr 1980: Convergent metamorphism of eclogite and garnet-bearing ultramafic rocks at Lien, West Norway. Nature 283, 470-472.
- Medaris, L.G. Jr 1980: Petrogenesis of the Lien peridotite and associated eclogites, Almklovdalen, Western Norway. Lithos 13, 339-353.
- Medaris, L.G. Jr 1984: A geothermobarometric investigation of garnet peridotites in the Western Gneiss Region of Norway. Contrib. Miner. Petrol. 87, 72-86.
- Menuge, J.F., 1988: The petrogenesis of massif anorthosites: a Nd and Sr isotopic investigation of the Proterozoic of Rogaland/Vest Agder, SW Norway. Contrib. Mineral. Petrol., 98: 363-373.

- Mercy, E.L.P. and O'Hara M.J. 1965: Chemistry of some garnet-bearing rocks from south Norwegian peridotites. *N.G.T.* 45, 323-332.
- Mercy, E.L.P. and O'Hara M.J. 1967: Distribution of Mn, Cr, Ti and Ni in co-existing minerals from ultramafic rocks. *Geochim. Cosmochim. Acta* 31, 2331-2341.
- Michot, J. & Michot, P., 1969: The problem of anorthosites: the South-Rogaland Igneous Complex, southern Norway. I: Isachsen, YW (red.): Origin of anorthosite and related rocks. *New York State Mus Sci Serv Mem.* 18: 399-410.
- Michot, J., 1961: The anorthositic complex of Håland-Helleren. *Norsk geologisk tidsskrift*, 41: 157-170.
- Michot, P., 1939: Les gisement d'ilmènite dans la région d'Egersund et Bjerkreim. *Ann. Soc. Géol. Belgique*, 63: 80-83.
- Michot, P., 1956: Les gisement des minerais noir de la région d'Egersund. *Ann. Soc. Géol. Belgique*, 79: 183-202.
- Michot, P., 1960: La geologie de la catazone: Le probleme des anorthosites, la palingenese basique et la tectonique catazonale dans le Rogaland meridional (Norvege meridionale). *Norges geologiske undersøkelse*, 212 g: 54 pp.
- Milnes, A.G, Wennberg, O.P., Skår, Ø. and Koestler, A.G. 1997: Contraction, extension and timing in the South Norwegian Caledonides; the Sognefjord transect. In Burg, J.P. and Ford, M. (eds): *Orogeny through time. Geol. Society of London Spec. Publ.* 121, 123-148.
- Moore, A.C. and Qvale, H. 1977: Three varieties of alpine-type ultramafic rocks in the Norwegian Caledonides and Basal Gneiss Complex. *Lithos* 10, 149-161.
- Mylius, H.G., 1977: Lagerstättenkundliche Untersuchungen in der Sudliche Vortsetzung der der Ilmenittlagerstätte Tellnes (Sudnorwegen). Upublisert Diplom-oppgave, Tekniske universitet, Clausthal, 106 sider.
- Mysen, B.O. 1971: Petrology and geochemistry of eclogite and surrounding rocks around Ulsteinvik on Hareidland, western Norway. Thesis Univ. Oslo.
- Mysen, B.O. and Heier, K.S. 1971: A note on the field occurrence of a large eclogite on Hareid, Sunnmøre, Western Norway. *N.G.T.* 51, 93-96.
- Mysen, B.O. and Heier, K.S. 1972: Petrogenesis of eclogites in high grade metamorphic gneisses, exemplified by the Hareidland eclogite, western Norway. *Contrib. Min. Petrol.* 36, 73-94.
- Mørk, M.B.E., 1985: A gabbro to eclogite transition on Flemsøy, Sunnmøre, Western Norway. *Chem. Geol.*, 50, 283-310.
- Mørk, M.B.E. 1985a: A gabbro to eclogite transition on Flemsøy, Sunnmøre, western Norway. *Chem. Geol.* 50, 283-310.
- Mørk, M.B.E. 1985b: Incomplete high P-T metamorphic transitions within the Kvamsøy pyroxenite complex, West Norway: a case study of disequilibrium. *J. Metam. Geol.* 3, 245-264.
- Mørk, M.B.E. 1986: Coronite and eclogite formation in olivine gabbro Western Norway: reaction path and garnet zoning. *Min. Mag.* 50, 417-426.
- Mørk, M.B.E. and Brunfelt, A.O. 1988: Geochemical comparisons of coronitic gabbro and eclogites: metamorphic effects and the origin of eclogite protoliths Flemsøy, Sunnmøre, Western Norway. *N.G.T.* 68, 51-63.
- Mørk, M.B.E. and Krogh, E.J., Eds 1987: Excursion guide for the eclogite field symposium in western Norway Bergen to Molde.
- Mørk, M.B.E. and Mearns, E.W. 1986: Sm-Nd systematics of a gabbro-eclogite transition. *Lithos* 19, 255-267.
- Nielsen, F.M. & Wilson, J.R., 1991: Crystallization processes in the Bjerkreim-Sokndal layered intrusion, south Norway: evidence from the boundary between two macrocyclic units. *Contrib. Mineral. Petrol.* 107: 403 - 414.

- Nielsen, F.M., 1992: Magmakammerprosesser belyst med utgangspunkt i Bjerkreim-Sokndal intrusjonen, Rogaland, Syd norge. Ph.D. thesis, Aarhus University.
- Nielsen, F.M., Campbell, I.H., McCulloch, M. & Wilson, J.R., 1996: A strontium isotopic investigation of the Bjerkreim-Sokndal layered intrusion, Southwest Norway. *J. Petrol.*, 37: 171-193.
- Nilsson, L.P. & Staw, J., 1996: XRF-feltmålinger ($\text{TiO}_2\text{-Fe}_{\text{total}}$) og magnetisk susceptibilitets-målinger på Fe-Ti-oksyd-mineraliseringer i den sydlige delen av Bjerkreim-Sokndal - intrusjonen, Sokndal kommune, Rogaland. NGU-rapport 96.048. (NGU/Titania A/S).
- Nilsson, L.P., Korneliussen, A., Gautneb, H., McEnroe, S. & Schiellerup, H. 1999: Titanium deposits in Norway. In Stanley et al. (eds) Mineral deposits: processes to processing. Proceedings of the fifth biennial SGA meeting and the tenth quadrennial IAGOD symposium, London 1999. Balkema, Rotterdam, 1137-1140.
- Nilsson, L.P. & Staw, J., 1997: Magnetiske bakkemålinger, petrofysiske lab. målinger samt X-Met (XRF) målinger på Mydland og i Bakkaområdet, Bjerkreim-Sokndal intrusjonen, Sokndal kommune, Rogaland. NGU-rapport nr. 96.160. (NGU/Titania A/S).
- O'Hara M.J. and Mercy, E.L.P. 1963: Petrology and petrogenesis of some garnetiferous peridotites. *Trans. Roy. Soc. Edinburgh* 65, 251-314.
- Olerud, S., 1995: Norges mineralressurser - produksjon og potensiale. NGU rapport nr. 95.164.
- Oxaal, J., 1916: Norsk Granit. NGU Publikasjon nr. 76.
- Paludan, J., 1995: Structural evolution of the Bjerkreim-Sokndal layered intrusion, SW Norway: Micro to macro scale studies. Ph.D. thesis, Aarhus University.
- Paludan, J., Hansen, U.B. & Olesen, NØ., 1994: Structural evolution of the Precambrian Bjerkreim-Sokndal intrusion, South Norway. *Norsk geologisk tidsskrift*, 74: 185-198.
- Pasteels, P. & Michot, J., 1975: Geochronologic investigation of the metamorphic terrain of southwestern Norway. *Norsk Geologisk Tidsskrift*, Volume 55, No. 2.
- Pearce, J. A., Harris, N. B. W. and Tindle, A.G. 1984. Trace element discrimination diagram for tectonic interpretation of granitic rocks. *Journ. of Petrol.* 25 956-983.
- Pinet, M. and Smith, D.C. 1985: Petrochemistry of opaque minerals in eclogites from the Western Gneiss Region, Norway: I. Petrology of the oxide microassemblages. *Chem. Geol.* 50, 225-249.
- Pognante, U. and Kienast, J.R., 1987: Blueschist and eclogite transformations in Fe-Ti gabbros: a case from the Western Alps ophiolites. *J. Petrology*, 28, 271-292.
- Powell, R., 1985: Regression diagnostics and robust regression in geothermometer/ geobarometer calibration: the garnet-clinopyroxene geothermometer revisited. *J. metamorphic Geol.*, 3, 231-243.
- Qvale, H. 1978: Geologisk Undersøkelse av et Kaledonsk Serpentinittfelt ved Baldersheim, Hordaland. Cand. Real. Thesis, Univ. Oslo, 252 pp.
- Reksten, K. 1985: En petrologisk studie av Eide-området, Romsdalshalvøya. Cand. Sci. oppgave, Geol. Inst, Univ. Oslo.
- Robins, B. & Wilson, J.R., 1992: Excursion guide to the Bjerkreim-Sokndal Intrusion, S.W. Norway. I: Duschesne, J.-C. (red.): The Rogaland intrusive massifs – an excursion guide. IGCP 290, Anorthosite conference, June 1992. s. 40-51.
- Robins, B., Tumyr, O., Tysseland, M. & Garmann, L.B., 1997: The Bjerkreim-Sokndal Layered Intrusion, Rogaland, SW Norway: Evidence from marginal rocks for a jotunite parent magma. *Lithos* 39: 121-133.
- Roelandts, I. & Duchesne, J.C., 1979: Rare-earth elements in apatite from layered norites and iron-titanium oxide ore-bodies related to anorthosites (Rogaland, S.W. Norway). in: Origin and distribution of the elements (L.H. Ahrens ed.), Pergamon Press: 199-212.
- Rolfsen, R., 1994: Hovedelementanalyse av mineralene i Tellnes-malmen. Upublisert rapport, Titania A/S.

- Rubie, D.C., 1990: Mechanisms of reaction-enhanced deformability in minerals and rocks. In: Barber, D.J. and Meredith, P.G. (Eds) *Deformation processes in minerals, ceramics and rocks*. Unwin Hyman, pp 262-295.
- Rutter, E.H. and Brodie, K.H., 1995: Mechanistic interactions between deformation and metamorphism. *Geological Journal*, 30, 227-240.
- Rønning, S., 1995: Helikoptermålinger over kartblad 1311-IV Sokndal. NGU-rapport nr. 95.120. (NGU/Titania A/S).
- Råheim, A. 1972: Petrology of high grade metamorphic rocks of the Kristiansund area. N.G.U. 279, 1-75.
- Råheim, A. 1977: A Rb-Sr study of the rocks of the Surnadal syncline. N.G.T. 57, 193-204.
- Sandøy, R. 1995: En beskrivelse av den mineralogiske og geokjemiske omvandlingen fra gabbro til skapolittførende bergart (ødegårditt) fra Ødegården i Bamble, Telemark. Hovedoppgave i ressursgeologi, NTH, Universitetet i Trondheim, 126 p.
- Sanetra, S. 1985: The Rødsand Fe-Ti-V deposits, Møre, Western Norway. *Nor. geol. unders. Bull.* 402, 39-49.
- Santarelli, N. 1989: Evolution structurale et metamorphique du socle precambrien de la chaine caledonienne scandinave dans le Nord-Oppland - Norvege. These de Doctorat d'Etat - Univ. Paris VII.
- Schiellerup, H., 1996: Fe-Ti mines and prospects in the Egersund area of the South Rogaland Igneous Province. Field report 1995. NGU rapport 96.051. (NGU/Titania A/S).
- Schiellerup, H., 1996: Further observations on Fe-Ti mines and prospects in the South Rogaland igneous province. Field report, 1996. NGU rapport nr. 96.159. (NGU/Titania A/S).
- Schmitt, H.H. 1960: Geologic field investigations in the Eiksund-Jøsak area, Sunnmøre, Norway. Report to NGU, Trondheim. Unpubl.
- Schmitt, H.H. 1963: Petrology and structure of the Eiksundsdal eclogite complex, Hareidland, Sunnmøre, Norway. PhD Thesis. Univ. Harvard. 323 pp.
- Schott, W., 1984: Lagerstättenkundliche Untersuchung im südlichen Teil des Lopolithen von Bjerkreim-Sokndal (Sud-Norwegen). Upublisert Doktor-avhandling, TU Clausthal, 1 - 104.
- Schärer, U., Wilmart, E. & Duchesne, J. C., 1996: The short duration and anorogenic character of anorthosite magmatism: U-Pb dating of the Rogaland complex, Norway. *Earth and Planetary Science Letters* 139, 335 - 350.
- Skjerlie, F.J. 1969: The pre-devonian rocks in the Askvoll-Gaular area and adjacent districts, Western Norway. N.G.U. 258, 325-359.
- Smith, D. C. 1988. A review of the peculiar mineralogy of the Norwegian coesite-eclogite province, with crystal-chemical, petrological, geochemical and geodynamical notes and an extensive bibliography. In: Smith, D.C. (ed): *Eclogite and Eclogite-facies Rocks*. Development in Petrology 12. Elsevier Science, Amsterdam. 1-206.
- Smith, D.C. 1971: A tourmaline-bearing eclogite from Sunnmøre, Norway. N. G. T. 51, 141-147.
- Smith, D.C. 1976: The geology of the Vartdal area, Sunnmøre, Norway and petrochemistry of the Sunnmøre eclogite. PhD Thesis. Univ. Aberdeen. Not available.
- Smith, D.C. 1980: Highly aluminous titanite in natural high pressure hydrous eclogite-facies rocks from Norway and Italy, and in experimental runs at high pressures. Abstract. 26th Int. Geol. Congress, Paris. Section 02.3.1. p 145.
- Smith, D.C. 1984: Coesite in clinopyroxene in the Caledonides and its implications for geodynamics. *Nature* 310, 641-644.
- Smith, D.C. 1988: A review of the peculiar mineralogy of the "Norwegian coesite-eclogite province", with crystal-chemical, petrological, geochemical and geodynamical notes and an extensive bibliography. In: *Eclogite and Eclogite-facies rocks*, D.C. Smith (ed), pp 1-206.

- Starmer, I.C. (1991): The Proterozoic evolution of the Bamble Sector shear belt, Southern Norway; correlations across southern Scandinavia and the Grenvillian controversy. *Precambrian Research* 49, 107-139.
- Strand, T. 1969: Geology of the Grotli area. *N.G.T.* 49, 341-360.
- Stubbergh, J., 1994. *Kjemi* nr. 6, 1994.
- Sundvoll, B., 1987: The age of the Egersund dyke-swarm SW Norway: Some tectonic implications. *Terra Cognita* 7, 2 - 3.
- Svensen, H., Jamtveit, B., Yardley, B., Engvik, A., Austrheim, H. & Broman, C. 1999: Lead and bromine enrichment in eclogite-facies fluids; extreme fractionation during lower-crustal hydration. *Geology* 27, 467-470.
- Taylor, K.A., Scanlon, T.J., Moore, D.E., Reaveley, B.J., 1996: The critical importance of high quality ilmenite for the TiO₂ pigment industry. I: 12th Industrial Minerals International Congress, Chicago 1996. *Industrial Minerals*.
- Titania A/S, 1992: Titania A/S 90 år, 1902 - 1992. Ilmenitten. Titania A/S.
- Torsvik, T.H., Sturt, B.A., Ramsay, D.M. and Vetti, V. 1987. The tectono-magnetic signature of the Old Red Sandstone and Pre-Devonian strata in the Håsteinen area, western Norway, and implications for the later stages of the Caledonian Orogeny. *Tectonics*, 6, 305-322.
- Tucker, R.D. 1986: Geology of the Hemnefjord-Orkanger area, south-central Norway, *N.G.U.* 404, 1-20.
- Tørudbakken, B. 1981: In Excursion B1, Excursions in the Scandinavian Caledonides (W.L.Griffin and M.B.Mørck), *Min.-Geol. Museum, Oslo*. 91p.
- Ulvik, A., Marker, M. & Erichsen, E., 1998: Pukkundersøkelser i Rekefjord. *NGU-rapport* 98.129. Norges geologiske undersøkelse.
- Vander Auwera, J. & Duchesne, J.C., 1990: Evidence of leuconoritic liquids in the EGOG massif-type anorthosite (Rogaland, Souterhn Norway) (Abstr.). *IGCP 290, Burundi Meeting 1990*.
- Vander Auwera, J. & Longhi, J., 1994: Experimental study of a jotunite (hypersthene monzodiorite): constraints on the parent magma composition and crystallisation conditions (P, T, fO₂) of the Bjerkreim-Sokndal layered intrusion (Norway). *Contrib. Mineral. Petrol.* 118: 60-78.
- Vander Auwera, J., Longhi, J. & Duchesne, J.C., 1998: A liquid line of descent of the jotunite (hypersthene monzodiorite) suite. *J. Petrol.* 39: 439-468.
- Versteeve, A., 1975: Isotope geochronology in the high-grade metamorphic precambrian of southwestern Norway. *Norges geologiske undersøkelse*, 318: 1-50.
- Vogt, J.H.L., 1910: Norges jernmalforekomster. *Norges geologiske undersøkelse*, 51: 132-138.
- Wanvik, J.E., 1998: Anortositt-ressurser i Indre Sogn og Voss. *NGU-rapport* 98.150. Norges geologiske undersøkelse.
- Waters, D.J. and Martin, H.N. 1993: Geobarometry in phengite-bearing eclogites. Seventh meeting of the European Union of Geosciences; abstract supplement. *Terra Abstracts*. 5,suppl. 1, 410-411.
- Weiss, D., 1986: Genetic implications of Pb isotopic geochemistry in the Rogaland anorthositic complex (southwest Norway). *Chem. Geol.*, 57: 191-199.
- Wielens, J.B.W., Andriessen, P.A.M., Boelrijk, N.A.I.M., Hebeda, E.H., Priem, H.N.A., Verdurmen, E.A.Th. & Verschure, R.H., 1980: Isotope geochronology in the high-grade metamorphic precambrian of southwest Norway: new data and reinterpretations. *Norges geologiske undersøkelse*, 359: 1-30.
- Wikstrøm, A. 1970: Electron microprobe studies of the alteration of omphacite in eclogites from the Nordfjord area, Norway. *N. G. T.* 50, 137-155.
- Wilmart, E., Demaiffe, D. & Duchesne, J.-C., 1989: Geochemical constraints on the genesis of the Tellnes ilmenite deposit, Southwest Norway. *Econ. Geol.*, 84: 1047-1056.

Wilson, J.R., Robins, B., Nielsen F., Duschene, J.C., Vander Auwera, J., 1966: The Bjerkreim-Sokndal layered intrusion, Southwest Norway. I: Cawthorn, R.G. (red.): Layering in igneous complexes. Elsevier, Amsterdam, s. 231-256.

Yardley, B.W.D. 1989: An introduction to metamorphic petrology. Longman. 248 p.

Zeino-Mahmalat, R., 1972: Untersuchungen an Plagioklasen aus dem Anorthosit-Komplex von Åna-Sira (Sudnorwegen). Upublisert avhandling, Techn. Univ. Clausthal. 140 p.