

Report

Field workshop in the Rogaland Anorthosite Province 8-12 July 2001

GEODE project

Ilmenite Deposits in the Rogaland Anorthosite Province

Subproject under the GEODE Fennoscandian Shield project

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Background. Purpose of the meeting

Geodynamics and Ore Deposit Evolution (GEODE) is an European Science Foundation (ESF) scientific programme (1998-2002) with the purpose to build a quantitative understanding on all scales of the geological processes that lead to the formation of world-class ore deposits suitable for exploitation. The GEODE scientific programme is built upon five projects, each relating to mineral provinces in Europe, which contain world-class ore deposits. GEODE's role is primarily to stimulate increased collaboration on research activities, including the funding of workshops.

The five projects focus on:

- The Alpine-Carpathian chain
- Ore deposits and geodynamics of the Southwestern Variscides
- Basin-hosted deposits
- The Urals mineral province
- The Fennoscandian Shield Precambrian province.

The project "Ilmenite deposits in the Rogaland Anorthosite Province" is a sub-project of the Fennoscandian Shield project. See further details at the websites

<http://www.gl.rhbc.ac.uk/geode/> and <http://www.ngu.no/prosjekter/Geode/index.htm>

The aim of the Rogaland field workshop were bring together earth scientists interested in:

- Evolution of the Rogaland anorthosite province as well as massif-type anorthosites in general
- Metallogeny of titanium deposits
- Relationships between the genesis of the various types of mineral deposits in the Rogaland anorthosite province and the overall geological evolution of the province
- The world class Tellnes ilmenite deposit; its geology and economic significance
- Identification of unresolved petrogenetic problems related to the Rogaland Anorthosite Province.

The meeting took place at the Lundheim Folkehøgskole at Moi, where the participants had good opportunity for both formal and informal discussions during the seminars and the field trips, at the meals and in the evenings. 54 geologists from 15 countries participated (see Appendix), representing a wide range of expertise from academic research institutions, geological surveys and mining companies. The importance of coming together over 5-6 days to review various aspects of the geological evolution of the province and its titanium deposits, and the discussions of unsolved geological problems, cannot be underestimated. After the meeting very positive responses have been received from a number of participants.

Purpose with this report is to give a summary of the workshop and point out subjects of significant scientific interest for continued research.

Abstract volume

The abstract volume is available as an NGU report no. 2001.042 "Abstracts – GEODE field workshop 8-12th July 2001 on ilmenite deposits in the Rogaland anorthosite province, S. Norway". This report is available from NGU, but can also be downloaded as a pdf-file from the GEODE Rogaland website <http://www.ngu.no/prosjekter/Geode/index.htm>.

Excursion guidebook

The excursion guidebook is available as NGU report 2001.029 (139 p.) "The Rogaland Intrusive Massifs – an excursion guide" by Jean-Clair Duchesne (editor). It is also available as a pdf-file at the GEODE Rogaland website <http://www.ngu.no/prosjekter/Geode/index.htm>. This guide is a significant document giving updated information on the geology and mineral resources of the Rogaland Anorthosite province.

List of contributors to the excursion guide:

- Jean-Clair Duchesne (University of Liège, Belgium)
- Bernard Bingen (Norsk Geologiske Undersøkelse, Trondheim, Norway)
- Olivier Bolle (University of Liège, Belgium)
- Daniel Demaiffe (Free University of Brussels, Belgium)

- Hervé Diot (University of La Rochelle, France)
- Robert Maquil (Geological Survey of Luxembourg, G.D. Luxembourg)
- Brian Robins (University of Bergen, Norway)
- Henrik Schiellerup (NTNU, Trondheim, Norway)
- Jacqueline Vander Auwera (University of Liège, Belgium)
- Edith Wilmart (University of Liège, Belgium, now at CEPT, CNRS, France)
- J. Richard Wilson (University of Aarhus, Denmark)

Seminars and poster exhibition

The seminars were held during the first two days of the workshop with poster sessions in the evenings. The presentations are listed in Table 1; see also the abstracts volume.

The first seminar day focused on the Rogaland anorthosite province including the Bjerkreim-Sokndal layered intrusion and the Tellnes ore deposit. The two invited speakers Donald Lindsley and Grant Cawthorn presented their lectures "Do Fe-Ti oxide magmas exist? Geology: Yes; Experiments: No!" and "Genesis of Magmatic Oxide Deposits - a View from the Bushveld Complex", respectively.

The second seminar day focused on Fennoscandia outside the Rogaland Anorthosite Province, the Ukrainian Shield, the East European Craton and North America.

See the abstract volume for further information on the presentations.

Table 1: Presentations held at the Rogaland field workshop 2001

Authors	Title	Presentation
Andersen T, Griffin WL, Pearson NJ & Andresen A	Sveconorwegian rejuvenation of the lower crust in south Norway	Lecture
Årebäck H	Concentration of ilmenite in the late Sveconorwegian norite-anorthosite Hakefjorden Complex, SW Sweden	Lecture
Bingen B and Stein H	Re-Os dating of the Ørdsalen W–Mo district in Rogaland, S Norway, and its relationship to Sveconorwegian high-grade metamorphism	Lecture
Bingen B, Austrheim H, Whitehouse M & Mansfeld J	Ilmenite–zircon relationships in meta-anorthosites. Example from the Bergen Arc (Caledonides of W Norway) and implications for zircon geochronology	Poster
Bogdanova S	AMCG magmatism and major tectonic events in the East European Craton	Lecture
Bolle O, Diot H, Lambert JM, Launeau P & Duchesne JC	Emplacement mechanism of the Tellnes ilmenite deposit (Rogaland, Norway) revealed by a combined magnetic and petrofabric study	Lecture
Brown L, McEnroe S & Smethurst M	Tectonic setting of the Egersund-Ogna Anorthosite, Rogaland, Norway, and the position of Fennoscandia in the Late Proterozoic	Poster
Cawthorn C	Genesis of Magmatic Oxide Deposits - a View from the Bushveld Complex.	Invited lecture
Charlier B & Duchesne JC	Whole-rock geochemistry of the Bjerkreim-Sokndal layered series: Bearing on crystallization processes of cumulus rocks	Poster
Chernet T	Effect of mineralogy and texture of sand and hard rock ilmenite in TiO ₂ pigments production by sulfate process, a case study on Australian ilmenite concentrate and Tellnes ilmenite concentrate, Norway.	Poster
Didenko PI, Kryvdik SG & Zagnitko VM	Ti, Mg and O isotopic composition in ilmenites from Ukrainian ore deposits as indicator of their crystallisation conditions	Poster
Duchesne JC & Vander Auwera J	Fe-Ti-V-P deposits in anorthosite complexes: the bearing of parental magma composition and crystallization conditions on the economic value	Lecture
Fershtater GB	Subduction related leucogabbro-anorthosite ilmenite-bearing series: an example of water rich high-temperature anatexis (Platinum belt of the Urals, Russia)	Lecture

Fershtater GB & Kholodnov VV	The Riphean layered intrusions of the Western Urals and related ilmenite-titanomagnetite deposits	Lecture
Gauthier M	Cambrian titaniferous paleoplacers deposited on a Iapetus ocean's shoal at the margin of the Grenville metallogenic province (Canadian Shield), and then metamorphosed during the Taconian orogeny of the Québec Appalachians	Lecture
Gautneb H	SEM elemental mapping and characterization of ilmenite, magnetite and apatite from the Bjerkreim - Sokndal layered intrusion	Poster
Gursky D., Nechaev S & Bobrov A	Titanium deposits in Ukraine focussed on the Proterozoic anorthosite-hosted massives.	Both
Hagen R	The mining of the Tellnes ilmenite deposit	Lecture
Hannah JL & Stein HS	Evidence from Re-Os for the origin of sulfide concentrations in anorthosites	Lecture
Hellström F	Accumulation of ilmenite in the post-Sveconorwegian Tuve dyke, SW Sweden	Poster
Kärkkäinen N	Gabbro hosted ilmenite deposits in Finland	Lecture
Korneliusson A	On ilmenite and rutile ore provinces in Norway, and the relationships between geological process and deposit type.	Poster
Kozłowski A & Wiszniewska J	The nelsonite problem: the origin by melt immiscibility	Lecture
Kryvdik S	Ilmenite deposits and mineralization in alkaline and subalkaline magmatic complexes of Ukrainian shield	Poster
Kullerud K	Geochemistry and mineralogy of the Tellnes ilmenite ore body	Poster
Lindsay DH	Do Fe-Ti oxide magmas exist? Geology: Yes; Experiments: No!	Invited lecture
McEnroe S, Robinson P & Panish PT	Aeromagnetic anomalies, magnetic petrology and rock magnetism of hemo-ilmenite- and magnetite-rich cumulates from the Sokndal Region, South Rogaland, Norway	Lecture
Meyer G	LA-HR-ICP-MS studies of ilmenite in MCU IV of the Bjerkreim-Sokndal intrusion, SW Norway	Poster
Mitrokhin AV	The gabbro-anorthosite massives of Korosten pluton (Ukraine) and problems evolution of parental magmas	Poster
Morisset CE	Mineralization in iron - titanium oxide minerals and apatite of the Lac Mirepoix ore deposit, Lac St-Jean Anorthosite Complex (Québec, Canada)	Poster
Nechaev S & Pastukhov V	Links between the Proterozoic anorthosite-rapakivi granite plutons and ore-forming events in the Ukrainian shield (ores of titanium, uranium, rare metal and gold)	Both
Perreault S	Contrasting styles of Fe-Ti mineralization in the Havre-Saint-Pierre anorthosite suite, Quebec's North Shore, Canada.	Both
Perreault S & Heaman L	The 974 Ma Vieux-Fort Anorthosite, Lower North Shore, Québec : the youngest anorthosite in the Grenville Province.	Lecture
Perreault S & Hebert C	Review of Fe-Ti and Fe-Ti-P205 deposits associated with anorthositic suites in the Grenville Province, Quebec	Poster
Robins B	Processes in the Bjerkreim-Sokndal magma chamber and the concentration of Fe-Ti oxides	Lecture
Robinson P, Kullerud K, Tegner C, Robins B & McEnroe S	Could the Tellnes ilmenite deposit have been produced by in-situ magma mixing?	Lecture
Schiellerup H, Lambert DD & Robins B	Sulfides in the Rogaland Anorthosite Province.	Lecture
Schumacher JC	Thermal modelling of the metamorphism of the Rogaland granulites	Lecture
Shumlyanskyy L	First approach to the petrology of the Kamenka peridotite-gabbro-anorthosite intrusion	Poster
Stein HJ, Hannah JL, Morgan JW, Scherstén A & Wiszniewska J	Parallel Re-Os Isochrons and High 187Os/188Os Initial Ratios: Constraints on the Origin of the Suwalki Anorthosite Massif, Northeast Poland.	Lecture
Stepanov VS	Ti, V, Pt, Pd and Au in Travyanaya Guba ore peridotites and their possible genetic relation with Belomorian Mobile Belt anorthosites	Poster
Stepanov VS & Stepanova AV	Precambrian anorthosites in the Belomorian Mobile Belt, eastern Fennoscandian Shield	Poster
Vander Auwera J, Longhi J & Duchesne JC	Some results on the role of P, T and fO2 on ilmenite composition	Lecture
Wilson JR & Overgaard G	Relationship between the Layered Series and the overlying evolved rocks in the Bjerkreim-Sokndal Intrusion, southern Norway	Lecture

During the seminar days, during the excursions and in the evenings, the following subjects experienced particular interest and discussion:

- Igneous genesis of ilmenite-rich rocks: Keynote speaker Donald Lindsley used oxide-rich "dikes" as an example where field evidence would suggest crystallization from an oxide-rich magma. He then proceeded, through the results of many experiments, to show that oxide-rich magmas cannot be created in the laboratory under any reasonable conditions and would therefore seem unlikely in nature, the sole exception perhaps being melts saturated in graphite. These results would imply that most oxide-rich igneous rocks must be derived from magmas of more normal composition by cumulus processes as yet poorly understood.
Keynote speaker Grant Cawthorn focused on how oxide minerals, particularly chromite and vanadiferous magnetite, can be concentrated in layered intrusions, using the Bushveld Complex as his example. He explored concepts related to magma mixing, including tests giving seemingly contradictory results. He also considered adcumulus growth during which silicate precipitation could be temporarily suppressed. His emphasis was on solving these problems using every physical and analytical tool available to the modern petrologist. The two lectures provided a firm basis for discussion both in the seminars and in the field, and the two speakers also contributed to lively discussions on the outcrops.
- Re-equilibration of ilmenite during cooling. Observations of MgO-content in ilmenite in the layered series of the Bjerkreim-Sokndal intrusion, indicates that the actual MgO-content in ilmenite often is lower than can be expected from a magmatic crystallisation standpoint. The favoured explanation is that a relatively slow cooling has allowed for reequilibration of ilmenite in which some of the magnesium exchanged with FeO in the surrounding silicates. This is of significant interest from an economic-geologic point of view; the lower MgO in ilmenite the better. The layered series of the Bjerkreim-Sokndal intrusion contains large volumes of low-grade ilmenite + vanadium-bearing titanomagnetite + apatite mineralisations; this is a very large, but low-grade mineral resource. A low MgO content (ca. 1 % MgO in certain parts of the intrusion) is a key parameter for this kind of deposit. However, some studies of near-end-member ilmenites in magnetite-rich cumulates suggest local Mg-enrichment by retrograde exchange with magnetite.
- Metamorphic effects of titanium deposits. It was pointed out that recrystallisation of titanium oxides during metamorphism, particularly high-grade metamorphism, often gave "cleaner" mineral grains with less intergrowths. However, others at the meeting pointed out, with reference to the poster by Tegist Chernet (see abstract volume), that hematite exsolution in ilmenite, common in many magmatic ilmenite deposits, can actually improve solubility of ilmenite during industrial sulphate process TiO₂-pigment production.
- The distribution of titanium provinces in relation to plate margins. It was shown that in Norway the various titanium provinces incl. the Rogaland Anorthosite Province, occur close to the Fennoscandian continental margin, i.e. at the western and southwestern margin of Baltica. It was then also pointed out that Fe-Ti deposits in the Urals occur at the eastern margin of the East European Craton (equivalent to the eastern margin of Baltica). This implies

that "geologic instability" at the continental margins favours the formation of titanium deposits (magmatic and metamorphic).

- The Tellnes Ilmenite Norite was the centerpiece of the conference and was visited on the second day of the field trips. The results of Lindsley (see above) and other features weigh strongly against genesis from an oxide melt, and some form of cumulate origin is favoured, either by intrusion of a mush previously accumulated elsewhere, or by in-situ accumulation in the present elongate steep-sided Tellnes body, perhaps enhanced by some form of magma mixing. Fabric studies in the ore body demonstrate a flat to gently plunging lamination indicative of longitudinal flow either of crystal mush or magma. The ilmenite-rich cumulates in magma replenishment zones of the Bjerkreim-Sokndal intrusion represent chemically well documented zones where ilmenite accumulation by gravity settling can be directly related to changing chemistry in a zone of magma mixing. Furthermore chemical similarity and similar cryptic variation of Tellnes silicates to those in the Bjerkreim-Sokndal intrusion, as well as melting experiments on Tellnes ores, strongly favour ore accumulation from jotunitic magma. The largest remaining gap in understanding is then in the physico-chemical mechanism by which ilmenite was concentrated from a melt that was not particularly rich in oxide components, and came to reside in a steep-sided floored dike-like body, lacking modal layering and of completely different shape from the laterally extensive layered intrusion.

Excursions

Excursion day 1:

This day (lead by Jean-Clair Duchesne) was devoted to anorthosites and associated titanium deposits in the western part of the province. A number of localities were visited, illustrating typical geological relations in the anorthosite diapirs incl. orthopyroxene and plagioclase megacrysts, inclusions of leuconorite in anorthosite, Visits to ilmenite deposits and associated rocks in the Kydlandsvatn area, and an anorthosite quarry at Sørskog where anorthosite is being mined for dimension stone.

Localities visited:

- Locality 1.2 Piggstein: The anorthositic-noritic complex (p.79 in the excursion guide).
- Locality 1.6 Sørskog: Dimension stone quarry (p.84 in the excursion guide)
- Locality 1.16 The Liåsen sector (p.89 in the excursion guide)

See also chapter 2 "The Egersund-Ogna massif" (by Jean-Clair Duchesne) in the excursion guidebook.

Excursion day 2: Titanium deposits in the Sokndal area

See Chapter 5 "The Iron-Titanium Deposits" by Jean-Clair Duchesne and Henrik Schiellerup) in the excursion guidebook.

Localities visited:

- Locality 5.8 The Tellnes deposit (p.70 in the excursion guidebook)
- Locality 5.6 The Storgangen deposit (p.72 in the excursion guidebook)
- Locality 5.5 The Flordalen deposit (p.74 in the excursion guidebook)

Excursion day 3:

This day was devoted to the Bjerkreim - Sokndal layered intrusion, and was lead by Brian Robins and Richard Wilson. Focus was on the characteristics of the various megacyclic units in relation to the evolution of the magma chamber by fractional crystallisation, magma recharge, hybridisation and assimilation of country rocks. Of particular interest from the mineral resource point of view are the observations of how and where apatite, ilmenite with low MgO contents and titanomagnetite with high V-contents occur in the layered series and the significance of magma mixing on the formation of ilmenite-rich cumulates

Localities visited:

- Locality 2.9: Basal contact of MCU IV (Mega Cyclic Unit IV), Storeknuten
- Locality 2.6: Contact of MCUs II AND III, Hågåsen
- Locality 2.7: Contact of MCUs II and III between Teksevatnet and Teksetjørni

See Chapter 3 *The Bjerkreim-Sokndal Layered Intrusion* (by Brian Robins and J. Richard Wilson) in the excursion guidebook. .

Excursion day 4:

Roughly 25 participants jointed an optional excursion across the contact zone of the Åna-Sira massif with the Apophysis and the envelope of migmatitic gneiss and through the Hydra anorthositic body and its jotunitic chilled margin.

Subjects for continued research

Based on the discussions during the meeting and some follow-up contacts afterwards, the following subjects are of particular interest for further research:

- Comparison of Proterozoic Fe-Ti provinces in Europe (Fennoscandian Shield, Ukrainian Shield, East European Craton) and North America. Particular attention should be paid to location relative to continental margins and major tectonic boundaries, age relationships, metamorphism, oxide mineral chemistry and economic significance.
- The tracking of magma evolution through silicate and oxide mineral variations should be continued at an invigorated pace, with a more thorough focus on the oxides themselves. Such work should be continued in the Bjerkreim-Sokndal

layered intrusion, both as a genetic guide and as a possible means to locate economic apatite-ilmenite-vanadiferous magnetite ores. Detailed studies should be carried out of the cryptic variation in the Tellnes and Storgangen ore bodies, as well as in other layered ilmenite deposits.

- Detailed modal studies and careful textural examination of the effects of mineral re-equilibration should be used to try to distinguish between primary precipitate minerals, minerals grown from interprecipitate liquids and subsolidus effects leading to grain coarsening, as well as to distinguish between dikes completely foreign to their surroundings and layers of oxide-rich cumulates that are an integral part of their setting. The significance of subsolidus equilibration for the minor- and trace-element composition of ilmenite should be further investigated.
- Trace element, and isotopic analyses of minerals and rocks should be continued in order to delineate magmatic consanguinity and the ultimate origin of the parental magmas. This should be combined with further experimental studies, for example on the role of Ti during partial melting of possible source rocks and the conditions necessary for the generation of relatively oxidised magma types.
- Further research is needed into the physical and chemical processes that lead to the extreme concentration of Fe-Ti oxides represented by orebodies. The significance of liquid immiscibility, crystal sorting by various means, mixing of disparate magmas and country-rock assimilation need to be investigated by detailed petrological studies of suitable cases as well as experimental investigations of particular ores.
- Zircon geochronology should take advantage of favourable occurrences both for precise dating of magmatic events and for constraining country-rock assimilation. Continued refinement of the zircon, monazite and molybdenite geochronology and thermal models for contact aureoles should provide a better understanding of the timing and duration of various processes, including ore formation.
- Understanding of rock magnetism in relation to mineral compositions, magma evolution, and thermal models should be increased, and used as a tool for magnetic exploration for additional deposits both in South Norway and elsewhere. Particular emphasis should given to explaining why the pronounced negative magnetic anomalies over pure ilmenite rocks are often much weaker than over norites with only 2-3% ilmenite. The answer to this question could have implications for magnetism on Mars and other planetary bodies in the solar system.

Conference proceedings

Before the meeting the organizing committee had decided that Jean-Clair Duchesne would be editor of a conference proceedings, but without deciding its form and where to have it published. During, as well as after, the meeting this was discussed, and it has now been decided by the organizing committee that the conference proceedings is to include

- Extended abstracts
- Full papers by the two invited speakers Donald Lindsley and Grant Cawthorn

- A new geological map of the Rogaland Anorthosite Province
- A combined map description and excursion guide
- An overview article of the mineral resources (all types) within the Rogaland Anorthosite Province.

This will be published in NGU Bulletin. Further information will be given separately to those who participated in the conference.

Appendix: Participants at the Rogaland GEODE field workshop 2001

Name	Institution	Address	Email
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