

NGU Report 2007.055
Engebøfjellet rutile deposit

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Authors: Korneliussen, A., Wanvik, J.E. and M.A.T.M. Broekmans			Client: Nordic Mining ASA	
County: Sogn og Fjordane			Commune: Naustdal	
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Summary:				
<p>Engerbøfjellet is a large rutile deposit within eclogite rock on the northern side of Førdefjord in Naustdal municipality, Sogn og Fjordane county, West Norway.</p> <p>The deposit comprises minimum 300 Mt (million metric tonnes) of eclogite rock containing 2.5-5 wt% rutile (TiO₂, titanium oxide). With an estimated average grade of 3.8 wt% rutile the entire ore deposit contains 11.4 Mt rutile. With a current rutile price at 675USD per tonne, the total in-situ value amounts to 8.6 billion USD. With conventional mineral separation processing with 50% recovery, the recoverable rutile represents a value of 4.3 billion USD. Improved mineral processing using novel techniques allows for significantly higher value production, perhaps up to 7.0 billion USD.</p> <p>It is likely that adjacent areas north of Førdefjord, particularly eastwards from Engerbøfjellet towards Naustdal including the known Steinkrossen deposit, contain additional large amounts of rutile-rich eclogite, similar to Engerbøfjellet. Thus, potential additional rutile resources on the north side of Førdefjord are very significant.</p> <p>In case of rutile extraction with 50% rutile recovery, roughly 98% of the ore comprises mine waste with main silicate constituents garnet, pyroxene, amphibole, etc. The mine waste can safely be deposited, for instance in the adjacent fjord at 300-400 m depth. However, both the bulk availability and the mineral composition of the waste material provide a major opportunity for the development of by-products, increasing value production while at the same time decreasing the environmental burden.</p>				
Keywords: Industrial minerals		Titanium		Rutile

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Appendix 1: Major element analyses of eclogite from Engebøfjellet cores.



Fig. 1: Helicopter view over Engebøfjellet from the SW.

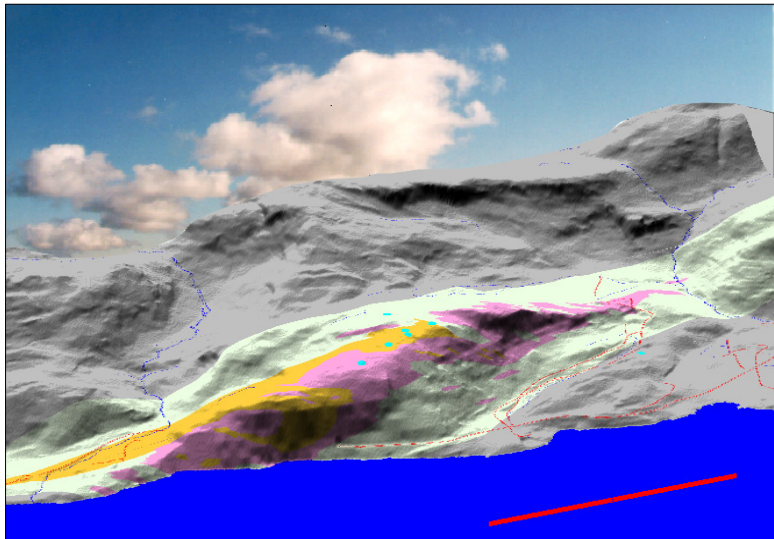


Fig. 2: Topographic model of Engebøfjellet, showing surface distribution of Ti-rich eclogite (pink). Scale bar on lower right is 1km.

1. INTRODUCTION

The Engebøfjellet rutile deposit (Fig. 1 and 2) is a 2.5 km long body of rutile-bearing eclogite situated in the mountain of Engebøfjellet on the north face of Førdefjord, western Norway.

This large titanium deposit was investigated for rutile in 1995-97 in collaboration between American titanium pigment producer DuPont, oil company Conoco (then a DuPont subsidiary; now ConocoPhillips), and NGU.

Based on 14,527 m of core drilling, the presence of an ore deposit estimated at 300 million tons of eclogite containing 3-5 wt% rutile was confirmed. Additional potential ore resources located nearby are large. The deposit is one of the largest mineral deposits in Norway and by far the most significant rutile deposit.

This report summarizes geological key data about the Engebøfjellet deposit, based on data collected and collated by NGU.

A technical-economical assessment is not provided, as NGU considers this outside its area of expertise.

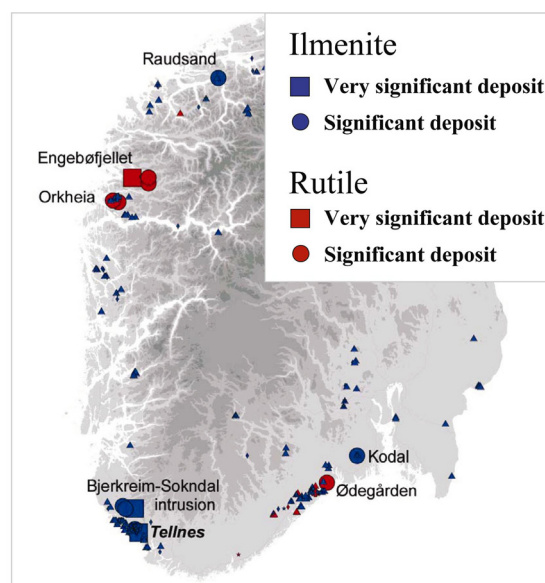


Fig. 3: Titanium deposits in S. Norway as registered in NGU database. Large symbols represent significant deposits. The Tellnes ilmenite deposit is in current production by Titania AS. Apart from Tellnes, the largest ilmenite resource is the Bjerkreim-Sokndal intrusion, while Engebøfjellet represents the most important rutile resource.

2. ON TITANIUM AND TITANIUM RESOURCES

Titanium has been called "the space-age metal" because of its high strength/weight ratio and its resistance to corrosion, compared to steel. This combination of high strength and superior corrosion resistance fuels the use of titanium metal in various and diverse applications including alloys and superalloys for aircraft and aerospace engines, deep-well drill pipe, corrosion resistant tubing for (petro-) chemical processing, sports articles like golf clubs, tennis rackets, cricket bats, bicycle frames and light-weight trekking equipment, high-tech watches, and for military purposes including aircraft and vehicles, personal equipment, smoke screens, pyrotechnics (eg. night flares), and firearms.

Architectural and/or civil engineering applications of titanium include façade cladding (eg. the Guggenheim Museum in Bilbao, Spain), and as non-corrosive concrete reinforcement in aggressive environments, eg. fertilizer plants, salts and acids process industry, and sea water in hot climate (eg. concrete moorings, jetties).

For its biocompatibility (non-toxic, non-reject), titanium is used in many medical applications including joint replacements (hip ball & socket), dental implants, allowing MRI-imaging as titanium is non-ferromagnetic. Titanium is furthermore used for surgical tools, wheelchairs, crutches and high-tech canes.

Despite its broad possible applications, the price of titanium metal is high, due to an energy-consuming and technically complicated refinement.

However, the main application of titanium is as titanium dioxide pigment (TiO_2 , either in rutile or anatase crystal form), which accounts for about 93% of the total titanium consumption. Because of its whiteness, high refractive index and light-scattering abilities, which give superior hiding power and

brightness, titanium dioxide is excellent as a filler and white pigment in coatings, paper, plastics and other materials.

In addition, anatase is recognized to have a photogenic effect in which it releases oxygen radicals under illumination. Thus, self-cleaning coatings have been developed for use in road tunnels (eg. Öresund Fixed Link) and kitchens, reducing pollution and obnoxious smells. Anatase has also been sputter-coated on glass to produce effective self-cleaning windowpanes for skyscrapers.

Titanium dioxide TiO_2 is a chemically inert compound with no known detrimental effect on health or environment. Titanium dioxide is therefore used as a whitening additive to a variety of foods, tablets and powders (including medicinal), toothpaste and sun-protective creams, referred to as “E 171” on the label.

Ilmenite ($FeTiO_3$) and leucosene (naturally leached and Fe-depleted ilmenite) and rutile (TiO_2) are the primary raw materials for titanium. Ilmenite and leucosene together contribute 93% and rutile 7% to world titanium consumption (metal and dioxide).

Titanium minerals are primarily mined from sand deposits mainly in tropical regions, where geological processes of weathering and cyclic erosion and (re-) deposition have naturally pre-concentrated the titanium minerals relative to the rock precursor. Ilmenite is being mined from “hard rock” in Canada, Norway (Titania AS at Tellnes) and China, while rutile and leucosene are exclusively being mined from sand deposits.

A substantial amount of world’s ilmenite production is upgraded to titanium slag; in Norway by Tinfos Titanium & Iron, based primarily on ilmenite from the Tellnes deposit (see below).

World resources of primary titanium raw materials ilmenite and rutile are very large, with main production in Australia (ilmenite and rutile from sand deposits), Canada (ilmenite from one hard rock deposit) and South Africa (ilmenite and rutile from sand deposits).

Although there is no direct global shortage on titanium, high-grade, high-quality ilmenite and rutile deposits are extraordinary and much sought-after by the mineral industry.

In Norway, mineable ilmenite reserves are located in the Tellnes deposit (Fig. 3, currently operated by Titania AS). The Engebøfjellet rutile deposit is a very large resource that has the potential to become of major future economic importance. In addition, very large resources of ilmenite + apatite + vanadium-rich magnetite occur within the Bjerkreim-Sokndal intrusion.

3. THE ENGEBØFJELLET RUTILE DEPOSIT

3.1 Exploration history

Assessments related to mining of eclogite for application as breakwater material and heavy aggregate are not included in this list.

- 1970’s and mid-1980’s: Elkem geologist Hans-Peter Geis was probably the first geologist to recognize the Engebøfjell eclogite as a rutile deposit. Additional sampling was done in collaboration between NGU and Elkem (1978-79) on rutile-bearing eclogites in Sunnfjord. Several companies were active at Engebøfjellet in the mid-80’s investigating the possibilities for rutile winning.
- In 1989, DuPont (world’s largest titanium pigment producer owning circa one fourth of global production) and NGU started an investigation and evaluation of Norwegian rutile, to locate deposits suitable for DuPont’s chlorination process pigment plants. Meanwhile, DuPont explored for rutile deposits worldwide. The project identified Engebøfjellet as the most favourable rutile deposit.

- 1995-97: DuPont/Conoco (then a DuPont subsidiary) and local Fjord Blokk came to agreement for joint effort to investigate Engebøfjellet rutile by surface sampling and geological mapping with additional core drilling and beneficiation testing. NGU was involved as an external consultant. DuPont discontinued the project after 1997 due to a change in company strategy. Conoco – now part of ConocoPhillips, maintained the mineral rights (utmål) for the deposit.
- 2000-2006: A number of mining companies visited Engebøfjellet, partly organised by “Rutilnett”, an informal working group organised through Naustdal municipality. Attention for the deposit re-emerged, and in 2006 several parties indicated their interest to purchase the Engebøfjellet deposit from ConocoPhillips. Nordic Mining was successful and initiated further development of the Engebøfjellet deposit.

NGU has been involved in most core drilling, sampling and geological investigations, and has done extensive analytical and mineralogical assessment of the core materials. In principle, all information is available from NGU and Nordic Mining. Cores are stored at NGUs drill-core storage facility at Løkken near Trondheim.

Beneficiation/mineral processing in testing was done in Sweden at MINPRO AB (comminution of a 75 tonne test batch of rutile ore) and in England, but most of the test work was carried out in USA at DuPont’s ilmenite mining operation in Florida. Information about this work is limited at NGU.

Compilation of analytical data on the extracted cores was done at DuPont’s main office in Wilmington, USA, including design of a 3D computer model of the deposit, modelling titanium grade distribution and calculation of extractable ore tonnages. This computer model is no longer operative.

3.2 Geological and mineralogical overview

The Engebø - Vevring area located on the northern side of Førdefjord, is characterized by a series of mafic rocks (eclogite and amphibolite) intercalated with grey gneisses (see Korneliussen et al. 1998 for more detailed information).

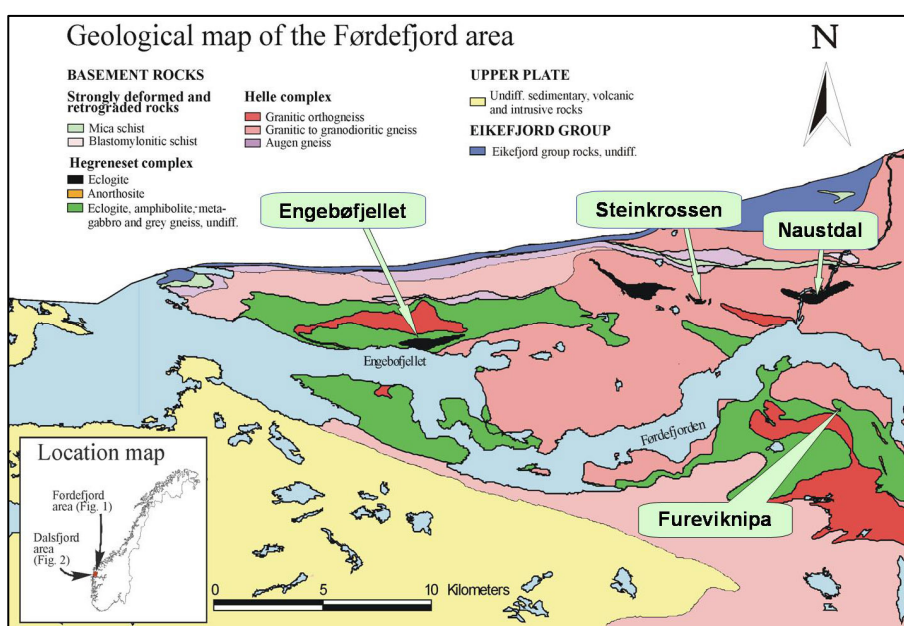


Fig. 4: Geological map of the Førdefjord area (adapted from Lutro & Ragnhildstveit 1997).

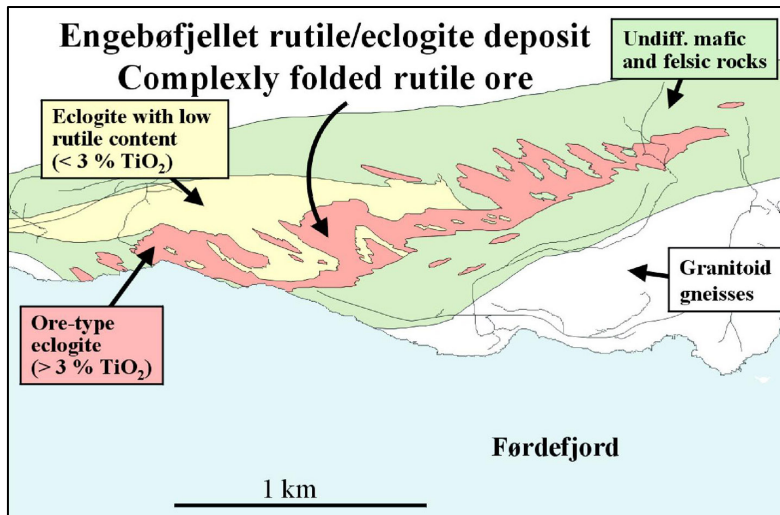


Fig. 5: Simplified geological map of Engebøfjellet (adapted from Korneliussen et al. 1998).

The Engebøfjell eclogite forms a 2.5 km long E-W-trending lenticular body. Although strongly affected by deformation, the eclogite has a contrasting massive character compared to the embedding country rock (Korneliussen et al. 1998). The body is believed to originally represent a Proterozoic gabbroic intrusion that was transformed to eclogite during high-pressure Caledonian metamorphism ~400 million years ago. During this episode, the ilmenite in the protolith was transformed to rutile, and Ti-rich parts of the body are now rutile ore.

According to the geological map of Engebøfjellet in Fig. 5, two main eclogite types can be distinguished based on different iron and titanium content:

- The ore bearing ferro-eclogite contains >14 wt% Fe₂O₃, >3 wt% TiO₂ and >25 vol% garnet. It has a more massive character than other eclogite varieties at Engebøfjellet, but some parts show banding and extensive folding. The largest volume of this rutile-rich eclogite occurs in the central and western parts of the deposit, and presumably continues below sea level. Typically, the contact with the other main eclogite type with low rutile content (leuco-eclogite; see below) is gradational and extends over several meters of intermediate composition. Sharp contacts between the two eclogite types occur only occasionally.
- Leuco-eclogite contains <14 wt% Fe₂O₃ and <3 wt% TiO₂, and less garnet. Locally, the ophitic gabbro protolith texture may be preserved.



Fig. 6: Photographs of different varieties of rutile-rich ferro-eclogite. Upper image: typical view of homogeneous undifferentiated eclogite.

Center image: Heterogeneous deformed eclogite, cross-cut by late quartz-veins (white).

Bottom image: Homogeneous eclogite cross-cut by a late quartz-clinopyroxene vein.

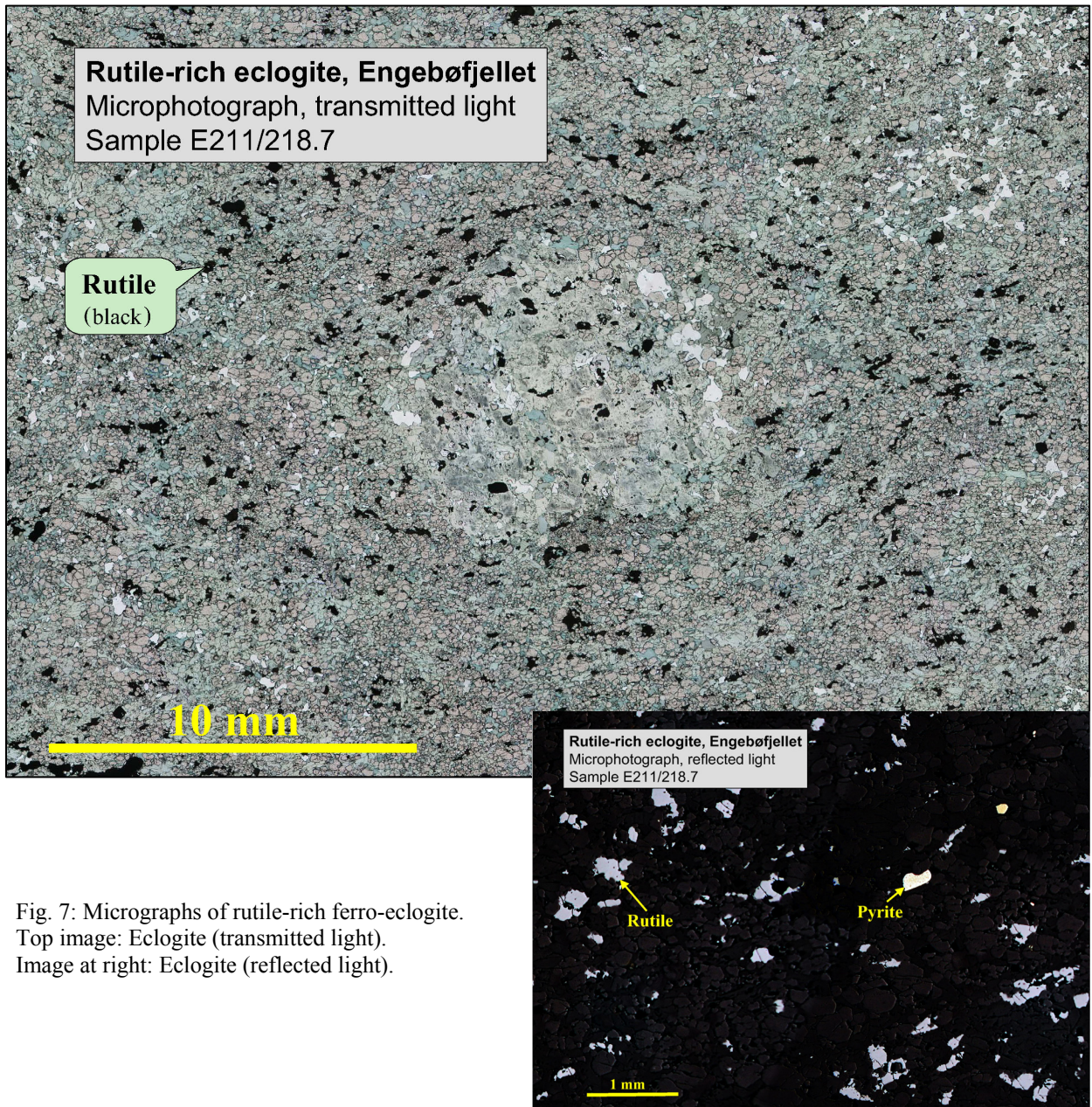


Fig. 7: Micrographs of rutile-rich ferro-eclogite. Top image: Eclogite (transmitted light). Image at right: Eclogite (reflected light).

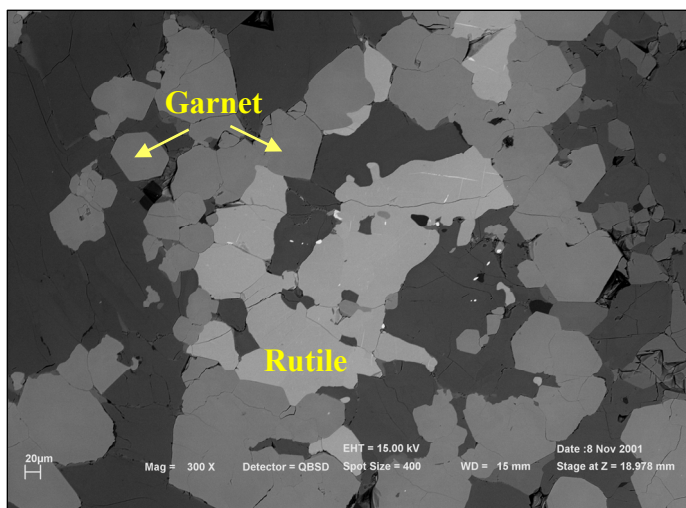


Fig. 8: SEM backscattered electron image of rutile-rich ferro-eclogite with subhedral garnet grains. The white spots are zircon. Scale bar at lower left 20 microns (0.02 mm).

3.3 Alteration of rutile to ilmenite

Retrograde metamorphism of eclogite causes rutile TiO_2 to react back to ilmenite FeTiO_3 and occasionally to titanite (sphene) CaTiOSiO_4 , as illustrated in Fig. 9-10. This reduces the quality of the rutile ore and the recoverability of the Ti-content. The eastern part of the deposit is most affected, while the central and western parts of the deposit are only retrograded to a minor extent. However, the extent of the retrogradation has not yet been investigated in adequate detail referring to a possible effect on mineral processing properties.



Fig. 9: Photo of eclogite with retrograde alteration veins (dark green to black). The rutile in such veins tends to be altered to ilmenite, as shown in Fig. 10.

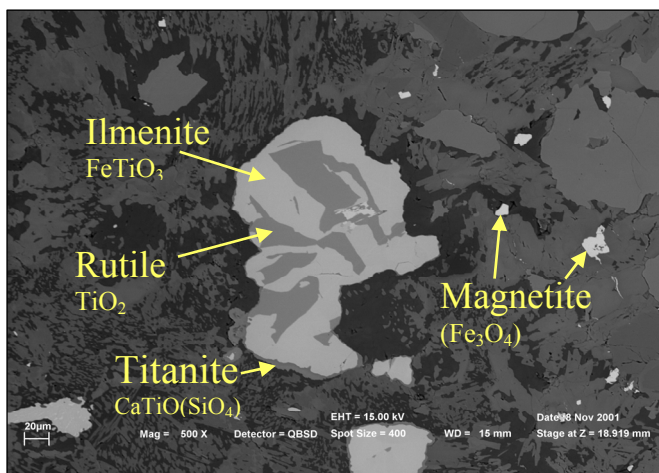


Fig. 10: SEM back-scattered electron image showing relic rutile in retrograde ilmenite and minor titanite.

This alteration is reserved to parts of the eclogite body that have experienced retrograde metamorphism, as illustrated in Fig. 9.

Secondary magnetite formed during the retrograde alteration of the rock causes a distinct increase in the rock's magnetic susceptibility, thus providing a convenient indicator for the degree of retrogradation.

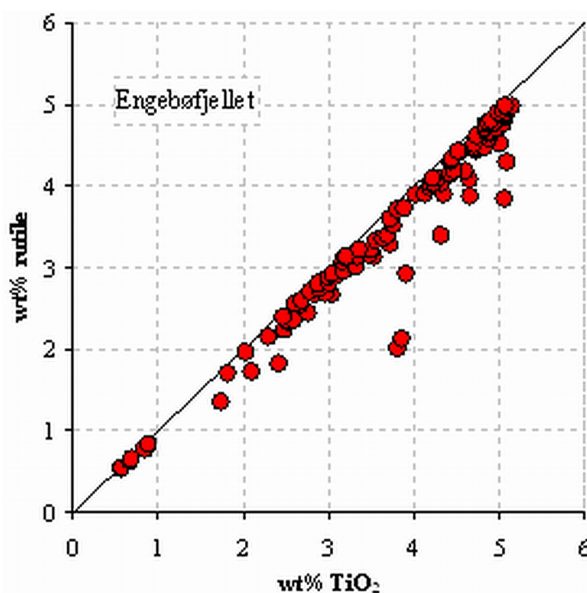


Fig. 11: Scattergram plot showing the relationship between wt% TiO_2 versus wt% rutile, based on data presented in Appendix 1. This figure illustrates that the bulk rock TiO_2 occurs predominantly in rutile, save a few exceptions far away from the bisectrix. These samples have enjoyed retrograde metamorphism in which rutile reacted to ilmenite+titanite. Samples on or near the bisectrix contain little or no ilmenite or titanite.

Analytical procedure: % Rutile = % TiO_2 (total, xrf-analyses) - % TiO_2 (acid soluble, icp-analyses). TiO_2 in silicate minerals is negligible.

3.4 Low uranium in rutile

In many rutile deposits all over the world, the high uranium content (50-200 ppm U) in the rutile concentrate is problematic, as uranium is expelled into the waste material from the TiO₂-pigment production and could thus pose an environmental problem.

In contrast, rutile from Engebøfjellet is practically free of uranium. Unpublished laser-ablation ICP-MS analyses by NGU reveal less than 1 ppm U in Engebøfjellet rutile. For comparison, the average earth crust contains 2-4 ppm U, depending on the source cited.

3.5 Rutile grain size

The titanium pigment producers require a rutile grain size in the concentrate to fall within a narrow range. Typically, >90 wt% of the rutile concentrate must exceed 75 µm (=0.075 mm), but some TiO₂-pigment producers require different specifications. The mineral concentrate produced by DuPont contained 90 wt% of rutile larger than 45 µm (=0.045 mm), compliant with their specification.

It is essential that the natural rutile grain-size be preserved as best as possible during comminution, to comply with ever changing quality specifications defined by the market.

3.6 CaO content

For TiO₂-pigment production using the chlorination process on rutile feedstock, strict quality requirements apply to the rutile concentrate in addition to grain size mentioned above. The CaO-content of the concentrate must not exceed 0.1 % CaO, slightly larger contents might be accepted under certain conditions.

Although rutile itself does not contain calcium, main eclogite minerals garnet, pyroxene and amphibole are all rich in calcium containing 8-15 wt% CaO. Inevitably, these minerals contaminate the rutile concentrate as relic impurities from mineral processing, resulting in a low but measurable CaO content. Thus, one major challenge in producing rutile concentrate is to keep the CaO-content below 0.1 wt%.

In rutile sand deposits, repeated weathering, erosion and (re-) deposition processes have effectively liberated and pre-concentrated rutile from the rock precursor whence calcium is not an issue. In contrast, rutile extracted from a hard rock deposit as Engebøfjellet must be liberated by mechanical crushing/milling, causing material loss and reducing recovery. This has in fact already been taken care of by natural processes that produce rutile sand.

This is the main reason why there is no hard rock rutile deposit in production in the world; it is technologically very difficult to produce a adequately pure rutile concentrate with sufficiently high overall recovery. In this respect, Engebøfjellet is a pioneering project.

3.7 Comminution and processing

In the beneficiation assessment by DuPont, the experiments provided a rutile concentrate fulfilling company specifications, with 40 wt% recovery, using combined magnetic and gravimetric separation. It was estimated that the procedure could be optimized to give 50 wt% recovery, and possibly 55-60 wt% if floatation was included as well, but at increased cost.

More recently, experiments with *electrical crushing* of rutile eclogite have been done with a greatly improved recovery up to 80 wt%. In addition, liberation degree increased while contamination

reduced with a similar amount, and the original grain size of the rutile was preserved in the final product.

Electrical crushing is not yet commercially available as an off-the-shelf technology. Yet, the experiments clearly demonstrate that high rutile recovery is possible, in combination with obtaining almost ideal specifications of the concentrate.

Developing adequate mineral processing procedures compliant with rutile grain size and CaO specifications combined with minimum recovery exceeding 50 wt%, poses the biggest challenge in the further development of the Engebøfjellet rutile deposit.

3.8 Cores and core log information

All together, 14527m drill core were sampled during 1995-97, altogether 49 holes with variable length from 99 to 440m. These cores are stored at NGUs core storehouse at Løkken.

Cores were logged on site during the drilling operation to identify the main character of the rock. The TiO₂ content was monitored directly in the field on core material using an Outokumpo X-Met portable XRF-instrument.

After transport to NGUs core storehouse at Løkken, cores were registered, documented and assessed using a range of methods (1996-97), including:

- Photo-documentation of each complete core;
- Direct analysis of TiO₂ and Fe₂O₃ using the X-Met portable XRF, four analyses per meter, overall 58 000 analyses. Due to large heterogeneity in distribution of TiO₂ at cm-dm scale as well as per-sample variation in mineral grain counting statistics (eg. Van Gaans et al 1986), the results vary considerably as shown in Fig. 12;
- Together with the X-Met analyses, magnetic susceptibility was measured with a portable instrument. Magnetic susceptibility increases by a retrograde reaction consuming rutile and producing ilmenite, as illustrated in Fig. 9 and 10. Thus, magnetic susceptibility provides an easy tool to assess the degree of retrogradation;
- A number of 10m long sections were analyzed at the NGU laboratory by XRF for reference purposes. Rutile content was determined in a separate procedure and was defined as: wt% rutile = bulk wt% TiO₂ – acid soluble wt% TiO₂. Bulk TiO₂ was determined by XRF, acid soluble TiO₂ by ICP-AES after digestion in hydrosulphuric acid. The results of these laboratory analyses were used to calculate instrumental correction factors for each borehole, and were applied to the existing X-Met XRF-analyses.
- Chemical and other data were submitted to DuPont in USA to build a 3D computer model of the Engebøfjellet deposit. This model was used in the further assessment of the deposit, and to calculate ore resources.
- Analytical results have been further assessed by NGU, as eg. Fig. 12. Field data (X-Met portable XRF) show considerable variation. The red line represents local analytical averages and reveals local variation in TiO₂ content along the core. Data from reference samples are indicated by purple (XRF-bulk wt% TiO₂) and green (wt% rutile) bars demonstrate the general reliability of X-Met analyses.

Engebøfjellet

ENV 26 (Version 3, Jan.98): Variation in TiO₂ and magnetic susceptibility along the core.

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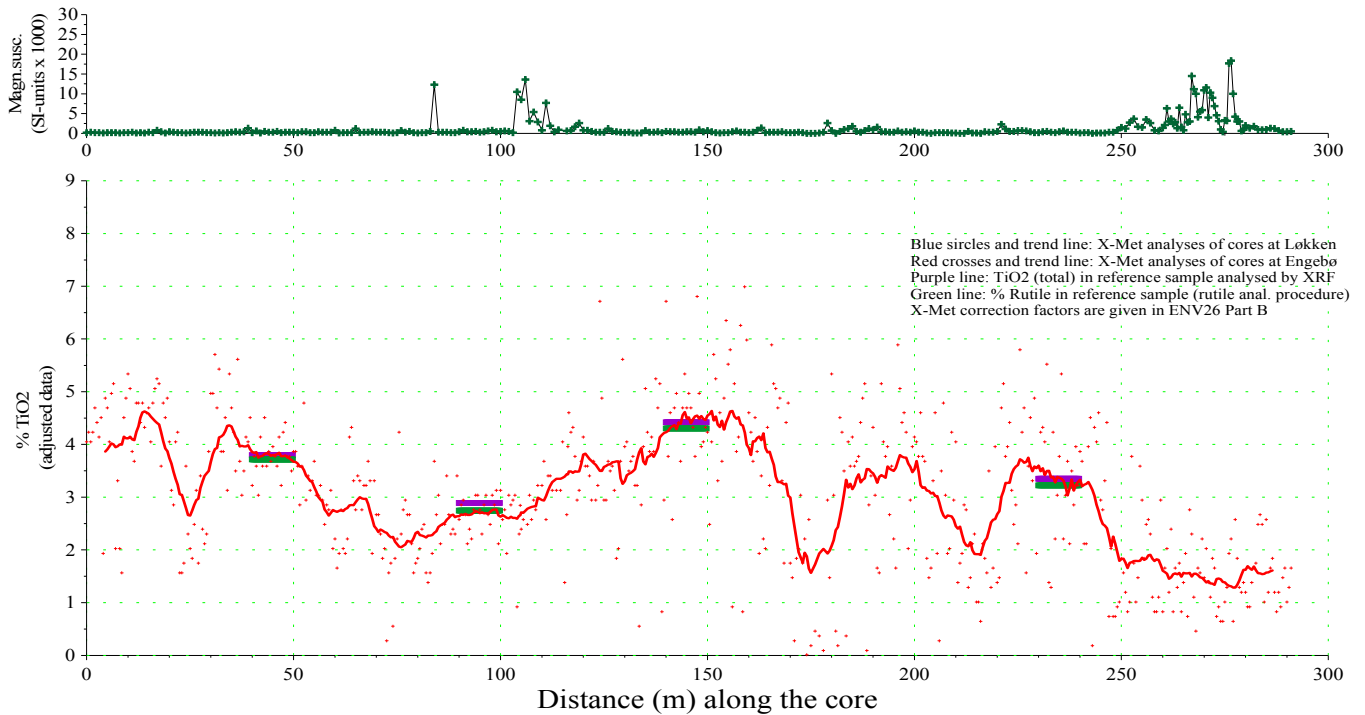


Fig. 12: Variation of magnetic susceptibility and TiO₂ content (in wt%) along the core of borehole 303. Similar graphs exist for all 49 boreholes. The red line represents local analytical averages and reveals local variation in TiO₂ content along the core. Data from reference samples are indicated by purple (XRF-bulk wt% TiO₂) and green (wt% rutile) bars demonstrate the general reliability of X-Met analyses. Coinciding bars imply all TiO₂ is present as rutile; a gap between bars indicates the presence of other Ti-minerals. In all four reference samples in this graph, more than 95 wt% of the titanium occurs as rutile.

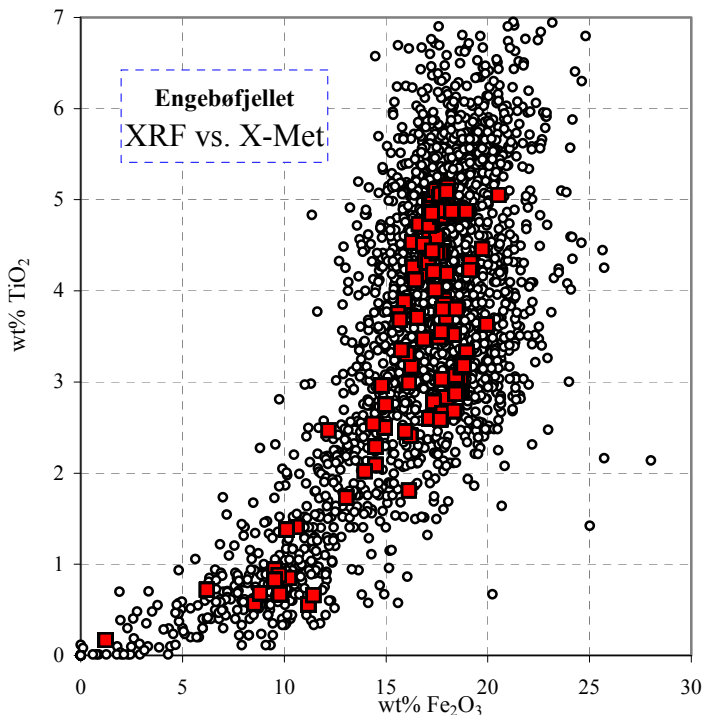


Fig. 13: Scattergraph of TiO₂ vs. Fe₂O₃, in weight percent. Grey dots: data from X-Met portable XRF, red squares: data from XRF at NGU-laboratory (complete results collated in Appendix 1).

The X-Met portable XRF data scatter over a wider range than the laboratory-XRF data, due to per-sample variation in mineral grain counting statistics (see eg. Van Gaans et al. 1986). In laboratory analysis, samples are pulverized and digested, averaging out above variation.

3.9 Resource estimation

The resource estimation presented by CIBC World Markets (Engebøfjellet Information Memorandum; report prepared in 2000) is 383 Mt (million tonnes) grading 3.96 % TiO₂ at a 3% TiO₂ cut-off, based on data from DuPont. This estimate does not incorporate the fact that the amount of TiO₂ is not equal to rutile content, due to the effects of retrograde alteration pointed out in Chapter 3.3.

Other companies that have visited and evaluated the Engebøfjellet deposit have established similar computer models based on the same raw data, giving lower resource numbers than those mentioned above; further details about these calculations are not available.

All in all, it is probable that the identified ore resource is lower than the CIBC number, but still large. A likely estimate is 300 Mt of rutile-rich eclogite with an average grade of 3.8 % rutile. Further analyses of available core materials and continued core drilling are required to specify the resource in more detail.

3.10 Summary of Engebøfjellet as a potential resource

Engebøfjellet has been identified as a resource of approximately 300 Mt of ore-grade eclogite. The TiO₂ content as rutile has been determined as 3.8 wt% on average, but may vary between 2.5-5 wt%.

In the main part of the deposit, more than 95 wt% of bulk rock titanium is comprised in rutile. Elsewhere in the deposit the rutile content is somewhat lower, due to retrograde metamorphic reaction consuming rutile to produce ilmenite±titanite (see Figs. 9-11).

The western part of the deposit continues below sea level and the additional “possible resource” is assumed to be large, in the order of 100 Mt or more. Thus, the total deposit may even exceed 400 Mt.

The presence of additional potential rutile resources has been indicated by a gravimetric survey combined with surface geological mapping eastwards from Engebøfjellet towards Naustdal (see summary in Korneliussen 2001).

Taking all the above into account, the total of confirmed and potential rutile resources north of Førdefjord between Engebøfjellet and Naustdal, are very significant.

Available analytical data were compiled at DuPont’s main office in Wilmington, USA, and were used to design a 3D computer model of the deposit, modelling titanium grade distribution and calculation of extractable ore tonnages. Though this model is no longer operational, it can easily be re-implemented using a standard mining software package.

4. DISCUSSION

NGU does not have the experience nor expertise necessary for a technical-economical assessment of potential ore deposits.

Nevertheless, Engebøfjellet is regarded as having great potential. Large-scale open pit mining will be required to achieve cost-effective operation, and a solution has to be found for the waste material produced. For environmental reasons, an industrial application is preferred over dumping, while adding further to the value production of the deposit.

The rutile raw ore value is approximately 26USD/tonne on site. Provided 50 wt% rutile recovery can be achieved, the net value is ~13USD/t, requiring large-scale mining and processing operation to minimize production cost per tonne final product.

DuPont planned for an annual production of 200 000 t of rutile concentrate per year, equivalent to approximately 135 million USD per annum. Smaller scale production was anticipated to tip the balance in an unfavorable direction towards higher costs per tonne.

Though exact values for total ore tonnage and average grade are subject to discussion, there is general consensus that the Engebøfjellet rutile deposit is “large enough” for a major mining operation. The variation in values largely reflects differences in experience and background of those involved in the assessment of the deposit. In NGU’s opinion, the presence of 300 Mt of ore containing 3.8 wt% rutile on average is realistic. Further analysis of existing cores, possibly combined with extraction of additional material will be required to specify the mineral resource in yet greater detail.

The deposit continues towards depth and the real tonnage is probably considerably larger than described above. In addition, there are promising implications for similar potential rutile resources in the mountains between Engebø and Naustdal, particularly at Steinkrossen 10 km east of Engebø. Taken together, confirmed and potential rutile resources north of Førdefjord are very large, providing excellent opportunities for large-scale industrial development.

The main challenge is to develop viable and cost-effective mineral processing, in addition to resolving waste deposition not discussed here. DuPont was successfully producing rutile concentrate, but only achieved 40 wt% recovery. Mineral processing must be optimized to attain minimum 50 wt% recovery, considered a realistic target using conventional comminution methods. Additional or alternative processing like acid leaching of silicate minerals is either expensive or not commercially feasible at present.

Regarding mineral processing, rutile grain size (see chapter 3.6) and calcium contamination (see chapter 3.7) of the rutile concentrate are essential issues. Both relate to comminution prior to further processing, and may inhibit further development if not properly taken care of.

Ideally speaking, comminution (1) preserves the natural grain size of the rutile, and (2) adequately liberates rutile from the embedding rock. Ad (1): excessive grinding destructing natural grain size may prevent further processing, while more rutile ends up as waste dust. Ad (2): relic rutile clinging to silicate minerals due to incomplete liberation also ends up as waste, whereas relic silicates clinging to rutile lead to contamination (CaO) of the final product. All of the above issues reduce recovery.

Adequate liberation probably poses the main reason for rutile not currently being mined from hard rock deposits. Sedimentary rutile in sand has been liberated by the action of natural weathering and erosion processes over extended (geologic) time, removing other minerals and effectively concentrating the rutile. Thus, rutile sand deposits rarely suffer from contamination by (Ca-) silicates.

Engebøfjellet is a pioneering challenge, demanding high competence and expertise, in addition to an innovative approach to be developed to its full potential. The vast size of confirmed and potential rutile resources at Engebøfjellet and its direct vicinity provide inspiring and promising prospects for substantial and sustainable industrial development. Interesting options for by-products may result in reduction of waste and emissions, as well as for value-added production.

5. REFERENCES

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Appendix 1: Bulk chemical compositions of eclogite from Engebøfjellet by XRF at NGU-laboratory, in wt%. Rutile content in wt% determined in separate procedure (further details in section 3.8).

Bh/From-To	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	MgO	CaO	Na ₂ O	K ₂ O	MnO	P ₂ O ₅	SUM	rutile	rut/TiO ₂
01/101-103	45,65	13,47	17,60	3,49	4,70	9,40	2,57	0,52	0,23	1,54	99,17	3,22	92,3 %
01/126-127	45,26	13,00	17,95	3,71	4,65	9,55	2,37	0,56	0,23	1,75	99,03	3,29	88,7 %
01/65-66	46,24	15,04	16,12	1,81	6,01	9,57	2,77	0,91	0,18	0,23	98,88	1,71	94,5 %
02/115-116	44,59	13,67	18,17	4,90	5,49	9,94	2,54	0,27	0,21	0,10	99,88	4,65	94,9 %
02/150-155	44,64	12,85	19,94	3,63	6,14	10,01	2,26	0,25	0,21	0,11	100,04	3,36	92,6 %
02/165-170	44,56	13,15	18,02	5,05	5,22	9,76	2,30	0,40	0,21	0,15	98,82	4,90	97,0 %
02/200-205	42,59	13,38	18,31	3,52	4,30	9,50	2,23	0,52	0,25	1,51	96,11	3,14	89,2 %
02/95-105	52,12	14,09	13,04	1,73	5,42	6,77	3,54	1,24	0,17	0,22	98,34	1,36	78,6 %
03/110-111	50,10	17,40	10,23	0,85	7,61	8,07	2,96	0,70	0,15	0,12	98,19	0,78	91,8 %
03/135-136	47,77	16,93	13,95	2,02	4,57	10,19	2,64	0,31	0,13	0,08	98,59	1,97	97,5 %
03/15-20	51,10	17,60	9,74	0,88	7,35	8,22	2,47	0,42	0,14	0,11	98,03	0,84	95,5 %
03/159-160	43,76	13,53	17,89	5,08	5,78	10,23	2,25	0,21	0,20	0,07	99,00	4,97	97,8 %
03/60-65	51,03	18,42	9,54	0,83	6,93	8,48	2,79	0,56	0,14	0,11	98,83	0,78	94,0 %
04/106-108	46,37	13,49	16,13	2,99	5,96	10,27	2,25	0,22	0,22	0,08	97,98	2,88	96,3 %
04/120-121	43,09	11,29	20,53	5,05	6,55	10,10	1,82	0,08	0,26	0,08	98,85	3,85	76,2 %
04/130-131	44,01	11,78	19,73	4,46	6,22	9,87	2,13	0,18	0,25	0,09	98,72	4,19	93,9 %
04/151-152	45,51	14,15	17,49	4,41	4,94	9,47	2,51	0,33	0,21	0,11	99,13	4,14	93,9 %
04/36-40	45,05	15,22	17,67	2,59	5,96	9,88	2,72	0,27	0,18	0,06	99,60	2,36	91,1 %
04/75-77	43,12	13,99	17,98	5,09	5,36	9,81	2,11	0,43	0,21	0,08	98,18	4,91	96,5 %
04/97-98	44,68	13,37	17,28	4,44	5,85	10,35	2,26	0,13	0,21	0,08	98,65	4,34	97,7 %
10/120-125	45,90	15,39	17,13	2,60	5,85	10,54	2,57	0,22	0,15	0,07	100,42	2,56	98,5 %
10/145-150	45,88	13,32	18,64	4,89	6,30	10,22	2,07	0,18	0,21	0,07	101,78	4,77	97,5 %
10/240-245	45,16	13,69	17,39	4,84	5,74	9,86	2,25	0,28	0,20	0,10	99,51	4,71	97,3 %
10/290-295	45,53	13,51	16,88	4,70	5,28	9,32	2,05	0,59	0,19	0,08	98,13	4,52	96,2 %
102/10-20	46,91	13,86	16,85	3,47	5,42	9,61	2,62	0,43	0,21	0,13	99,51	3,16	91,1 %
102/120-130	47,06	12,98	17,97	2,83	6,31	9,74	2,05	0,38	0,19	0,08	99,59	2,68	94,7 %
102/180-190	44,42	12,50	17,13	4,71	6,01	9,70	2,31	0,38	0,20	0,08	97,44	4,47	94,9 %
102/250-260	45,00	13,70	17,16	4,64	5,46	9,37	2,63	0,36	0,20	0,09	98,61	4,08	87,9 %
103/110-120	43,70	12,87	18,96	3,33	6,61	10,48	2,14	0,30	0,20	0,09	98,68	3,14	94,3 %
103/220-230	46,05	13,88	17,33	2,78	6,19	9,94	2,50	0,34	0,18	0,07	99,26	2,71	97,5 %
103/360-370	44,73	13,47	17,12	4,65	5,68	9,54	2,45	0,38	0,20	0,10	98,32	3,88	83,4 %
103/50-60	50,49	16,78	9,79	0,67	8,32	7,84	2,63	0,48	0,15	0,11	97,26	0,63	94,0 %
104/200-210	45,03	14,03	17,80	2,66	6,25	10,12	2,48	0,27	0,18	0,08	98,90	2,55	95,9 %
104/330-340	44,28	13,38	19,15	4,31	6,56	10,42	2,31	0,26	0,21	0,08	100,96	4,03	93,5 %
104/90-100	43,61	13,56	17,75	4,43	6,07	10,09	2,50	0,41	0,21	0,08	98,71	4,33	97,7 %
107/190-200	45,24	13,79	18,65	3,04	6,41	10,06	2,33	0,29	0,20	0,08	100,09	2,93	96,4 %
107/50-60	49,94	14,71	11,19	0,56	11,21	7,36	2,01	0,29	0,18	0,08	97,53	0,54	96,4 %
108/130-140	43,81	12,75	19,12	4,23	6,66	10,40	2,24	0,26	0,20	0,07	99,74	4,04	95,5 %
108/200-210	46,29	13,93	17,73	3,03	5,69	9,25	2,59	0,47	0,22	1,07	100,27	2,68	88,4 %
108/340-350	44,61	13,14	17,45	5,08	6,05	9,70	2,44	0,42	0,20	0,07	99,16	4,30	84,6 %
108/50-60	51,05	19,62	8,55	0,57	7,35	9,09	2,74	0,30	0,13	0,10	99,50	0,55	96,5 %
109/140-150	47,96	13,54	15,91	3,88	4,94	8,89	2,74	0,70	0,20	0,14	98,90	3,73	96,1 %
109/200-210	44,92	13,42	17,65	5,03	5,39	9,52	2,45	0,41	0,20	0,09	99,08	4,87	96,8 %
11/140-150	44,65	14,07	18,70	2,90	6,06	10,14	1,85	0,29	0,19	0,06	98,91	2,80	96,7 %
11/200-210	44,97	13,38	17,16	4,83	5,48	9,81	1,98	0,36	0,19	0,06	98,22	4,76	98,6 %
110/110-120	49,75	14,79	14,49	2,09	5,44	8,89	3,13	0,83	0,15	0,08	99,64	1,73	82,8 %
110/170-180	43,95	12,66	17,26	4,95	5,99	10,12	2,46	0,33	0,20	0,09	98,01	4,77	96,4 %
110/290-300	44,56	13,26	17,14	5,00	5,36	9,39	2,44	0,50	0,19	0,09	97,93	4,52	90,4 %
111/200-210	44,22	13,38	17,47	4,59	5,97	9,87	2,30	0,40	0,20	0,11	98,51	4,19	91,2 %
111/330-340	46,07	13,78	16,33	4,26	5,31	9,19	2,74	0,47	0,19	0,11	98,45	4,09	96,1 %
111/60-70	50,60	18,48	8,81	0,68	7,25	8,80	2,81	0,35	0,13	0,13	98,04	0,66	97,1 %
112/180-190	44,11	13,22	17,20	4,97	5,99	9,87	2,38	0,38	0,20	0,09	98,41	4,81	96,7 %
112/260-270	46,78	14,09	16,19	2,41	5,89	9,60	2,55	0,40	0,16	0,09	98,16	1,83	75,8 %
112/360-370	45,48	13,48	17,01	4,42	5,75	9,30	2,17	0,74	0,19	0,12	98,66	4,15	94,0 %
113/170-180	47,44	11,66	17,86	3,90	4,04	8,32	2,70	0,88	0,24	1,21	98,25	2,92	75,0 %
113/240-250	43,99	13,51	18,49	3,00	6,46	9,99	2,50	0,26	0,19	0,10	98,49	2,81	93,7 %
114/100-110	47,27	11,68	17,87	3,85	4,01	8,19	2,88	0,51	0,21	1,22	97,69	2,13	55,4 %

Bh/From-To	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	MgO	CaO	Na ₂ O	K ₂ O	MnO	P ₂ O ₅	SUM	rutile	rut/TiO ₂
12/270-280	44,71	13,54	17,26	4,98	5,51	10,19	2,07	0,28	0,20	0,08	98,82	4,91	98,5 %
12/370-380	45,13	13,59	17,22	4,73	5,18	9,87	1,97	0,39	0,20	0,08	98,36	4,62	97,7 %
13/100-105	43,18	12,57	18,43	4,85	5,89	10,12	2,03	0,19	0,20	0,07	97,53	4,66	96,1 %
13/130-140	44,01	13,71	18,02	5,06	5,16	9,73	2,02	0,31	0,20	0,07	98,29	4,99	98,6 %
13/150-160	43,88	13,40	17,87	4,90	5,49	10,16	2,01	0,23	0,20	0,08	98,22	4,81	98,2 %
13/180-181	44,17	13,93	16,62	4,73	4,95	9,50	2,09	0,66	0,18	0,07	96,90	4,46	94,3 %
13/182-183	43,40	13,72	17,44	5,10	5,26	9,85	2,05	0,45	0,20	0,07	97,54	4,95	97,1 %
13/190-200	44,38	13,01	17,30	4,88	5,75	9,85	1,95	0,43	0,21	0,08	97,84	4,67	95,7 %
13/230-240	45,30	13,07	18,42	3,07	5,91	10,12	1,78	0,29	0,19	0,05	98,20	2,90	94,5 %
13/257-258	43,80	13,39	18,68	3,16	5,87	9,91	1,87	0,38	0,19	0,07	97,32	3,08	97,3 %
13/259.1-260	40,71	13,71	12,18	2,47	5,39	10,22	0,17	2,78	0,15	0,61	88,39	2,24	90,7 %
202/180-190	48,36	13,19	14,78	2,96	5,75	9,36	2,61	0,37	0,19	1,15	98,72	2,69	90,9 %
202/20-30	47,13	13,42	16,55	3,71	5,64	9,78	2,50	0,41	0,21	0,11	99,46	3,60	97,0 %
202/70-80	46,31	14,27	17,42	4,01	5,34	9,58	2,59	0,38	0,22	0,13	100,25	3,90	97,3 %
203/170-180	49,09	14,21	14,98	2,75	5,21	9,02	2,74	0,66	0,20	0,11	98,97	2,45	89,1 %
203/20-30	45,71	14,11	17,04	4,18	5,53	9,24	2,92	0,39	0,21	0,15	99,48	3,99	95,5 %
204/10-20	45,47	13,97	17,98	4,19	5,47	9,67	2,58	0,22	0,22	0,12	99,89	4,03	96,2 %
204/130-140	47,08	13,05	15,59	3,75	5,58	9,78	2,62	0,40	0,20	0,11	98,16	3,52	93,9 %
207/110-120	43,69	12,57	17,99	5,04	6,19	10,21	2,46	0,24	0,21	0,08	98,68	4,77	94,6 %
207/130-140	44,21	13,65	17,29	4,96	5,92	9,88	2,36	0,35	0,19	0,09	98,90	4,71	95,0 %
207/60-70	44,48	13,74	18,82	3,20	6,31	10,20	2,28	0,33	0,20	0,08	99,64	3,14	98,1 %
208/130-140	47,34	13,40	16,28	4,53	5,81	9,35	2,32	0,71	0,19	0,09	100,02	4,42	97,6 %
208/270-280	46,78	12,64	17,11	4,72	5,38	9,14	2,32	0,38	0,19	0,10	98,76	4,44	94,1 %
208/50-60	46,66	15,41	14,94	2,50	5,58	9,12	2,44	1,10	0,16	0,33	98,24	2,35	94,0 %
209/150-160	44,58	13,44	17,61	5,03	5,96	10,17	2,74	0,30	0,19	0,08	100,10	4,94	98,2 %
209/90-100	44,61	13,64	18,81	3,18	6,57	10,52	2,27	0,19	0,19	0,08	100,06	3,13	98,4 %
210/100-110	45,92	16,63	15,93	2,46	5,28	10,73	2,63	0,27	0,15	0,08	100,08	2,40	97,6 %
210/240-250	44,51	13,58	17,68	4,82	6,25	10,36	2,53	0,25	0,20	0,09	100,27	4,48	92,9 %
210/340-350	46,37	14,01	16,25	3,17	5,87	9,37	2,64	0,54	0,21	0,15	98,58	2,96	93,4 %
211/130-140	47,56	11,49	17,77	3,80	4,00	7,89	2,44	1,05	0,25	1,20	97,45	2,02	53,0 %
211/210-220	44,84	13,64	16,92	4,34	5,26	9,63	2,64	0,38	0,21	0,14	98,00	3,90	90,0 %
211/310-320	43,06	12,96	17,80	5,03	5,87	9,82	2,37	0,31	0,20	0,12	97,54	4,85	96,5 %
211/410-420	44,34	13,29	17,08	4,31	6,06	9,88	2,35	0,43	0,21	0,12	98,07	3,40	78,9 %
212/170-180	45,76	14,13	16,44	4,12	5,39	9,61	2,72	0,39	0,21	0,14	98,91	3,91	94,9 %
212/270-280	46,90	13,82	15,68	3,68	5,11	8,45	2,53	0,72	0,19	0,13	97,21	3,40	92,3 %
212/70-80	44,15	13,46	17,20	4,90	6,02	10,10	2,42	0,25	0,19	0,10	98,79	4,81	98,1 %
213/130-140	46,01	14,49	14,49	2,29	6,17	9,43	2,79	0,59	0,20	0,22	96,68	2,16	94,2 %
213/210-220	46,74	13,48	16,05	3,31	5,34	9,48	2,55	0,52	0,21	0,13	97,81	3,01	91,0 %
213/40-50	43,86	13,13	17,57	4,88	5,71	9,93	2,42	0,37	0,21	0,12	98,20	4,67	95,7 %
214/200-210	43,74	12,35	18,94	4,87	6,07	9,94	2,26	0,15	0,24	0,13	98,69	4,59	94,2 %
214/310-320	45,73	14,22	14,37	2,54	5,84	9,29	2,80	0,87	0,19	0,56	96,41	2,33	91,9 %
214/40-50	44,46	13,60	17,15	4,86	5,92	10,28	2,47	0,27	0,20	0,12	99,33	4,78	98,4 %
301/100-110	44,38	14,25	18,34	2,68	6,51	10,42	2,36	0,20	0,18	0,08	99,40	2,60	97,1 %
301/190-200	44,70	13,79	17,34	4,21	5,34	9,73	2,56	0,28	0,22	0,71	98,88	4,10	97,3 %
301/40-50	43,94	12,91	18,24	4,87	6,19	9,75	2,27	0,28	0,20	0,09	98,74	4,76	97,7 %
302/190-200	43,53	12,96	17,69	5,06	6,31	10,19	2,29	0,21	0,21	0,10	98,55	4,84	95,7 %
302/30-40	44,74	13,58	16,83	4,51	5,90	9,79	2,50	0,43	0,19	0,09	98,56	4,43	98,2 %
302/330-340	43,82	13,52	18,05	5,14	5,65	9,88	2,33	0,32	0,21	0,11	99,03	4,98	96,9 %
303/140-150	44,75	13,30	17,66	4,42	6,02	9,62	2,28	0,31	0,21	0,33	98,90	4,30	97,4 %
303/230-240	47,56	13,81	15,74	3,35	5,51	9,10	2,69	0,52	0,19	0,13	98,60	3,22	96,2 %
303/40-50	44,55	13,16	18,45	3,80	6,29	10,06	2,29	0,30	0,21	0,11	99,22	3,71	97,8 %
303/90-100	44,23	13,70	18,54	2,89	6,54	10,31	2,35	0,26	0,18	0,08	99,08	2,74	95,0 %
304/200-210	44,31	13,55	17,24	4,85	5,89	9,97	2,50	0,34	0,20	0,13	98,98	4,65	95,9 %
304/330-340	44,39	13,34	17,72	3,55	5,54	9,65	2,58	0,33	0,23	1,42	98,75	3,33	93,9 %
304/80-90	44,49	14,00	18,42	2,87	6,46	10,28	2,42	0,25	0,19	0,10	99,48	2,81	97,9 %
Average	45,54	13,80	16,81	3,76	5,85	9,64	2,40	0,43	0,20	0,22	98,64	3,52	93,0%