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Summary of knowledge about Norwegian anorthosite prospecting ï in relation to Greenland anorthosites

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REPORT

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Summary:

This report gives an overview of Norwegian prospecting on anorthosites, with emphasis on the calcic types dominant in the Inner Sogn-Voss area of Western Norway. The high aluminium content of these large anorthosite bodies by the Sognefjord has made them the target of potential alternative sources for the aluminium-industry. In several phases during the last 90 years major Norwegian companies have done extensive geological investigations with this aim. The Sogn anorthosites contain a plagioclase with labradorite-bytownite composition, in the dominating range of 60-78% anorthite.

Many large Greenland anorthosites (An_{60-90}) prove to be somewhat higher in both acid solubility and aluminium content, thus giving them a favour to the Norwegian ones.

The large anorthosites in Rogaland (SW Norway) have lower aluminium content and are thus not interesting as an aluminium raw material. The titanium-rich ilmenite bodies and some alternative uses for this andesine-labradorite anorthosite (An_{40-55}) are thus covered in less detail.

Field relationships with regard to mineralogical and processing considerations are presented and some of the relevant process alternatives and the scope of potential end uses are given.

Keywords:	Industrial minerals	Anorthosite
Mineral resources		

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1. INTRODUCTION

This report was written as a result of an inquiry by Christian Knudsen at GEUS to NGU in connection with planned investigations of anorthosites in Greenland for potential industrial end uses. The many anorthosite areas, especially in Western Greenland, have been given only a preliminary investigation in this connection, and with the high-calcium type of anorthosites predominant in this coastal area it is of relevance to gain access to experience from the long-term investigations of calcium-type anorthosites in Western Norway. NGU consented to this request and an overall summary of the accumulated Norwegian knowledge from anorthosite prospecting in Norway is the main aim of this report. NGU is headquartered in Trondheim which is situated almost equally as far north as Nuuk, the capital of Greenland, although climatic conditions are somewhat different.

Fig. 1 Relative geographic positions of Greenland and Norway

2. MAIN NORWEGIAN ANORTHOSITES AND QUARRIES AND MINES IN PRODUCTION

Anorthositic rocks are present in various parts of Norway (red marks in figure 2) and quarrying has been done in 4 different areas. The two main anorthosite areas are the Proterozoic 700 km^2 inner Sogn/Voss province (SAP) and the 500 km^2 Rogaland province (RAP).

The Sogn massifs are well-known for their high calcium-aluminium type (An_{50-78}). Major parts of these massifs have this high An (anorthite) containing anorthosite, but the single plant in operation (Gudvangen stein) is a mine in altered white rock. The altered rock has low-An plagioclase but the high aluminium content is still intact, giving the needed high Al values attractive to their main customer, European Rockwool factories. The whiteness of the rock and very good technical properties makes it favourable as additive in special types of light asphalt.

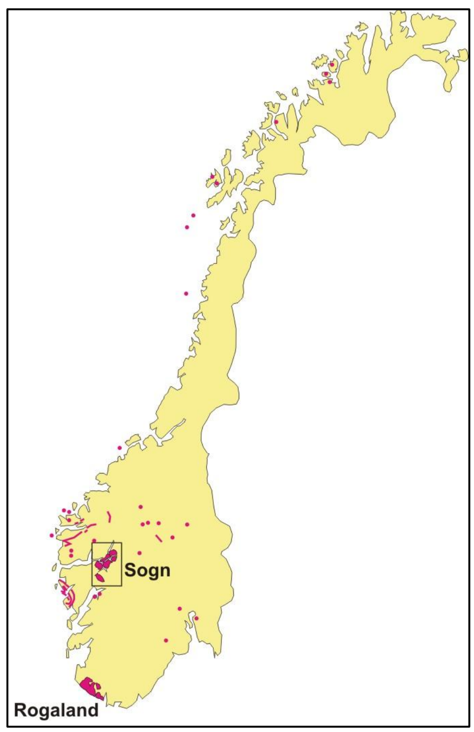

Fig. 2 Anorthosite localities in Norway

The Rogaland anorthosites are more sodic (An_{40-55}) and an unaltered brown variety with attractive blue schiller effect in large grains is quarried and exported as decorative dimension stone. A white, altered type is quarried at 4 locations in RAP and exported for road asphalt and filler purposes.

Table 1 Chemistry of unaltered anorthosite in the two main Norwegian provinces

	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	An content of primary plagioclase	Acid solubility of Al_2O_3 in unaltered anorthosite
Sogn-Voss	49-50	30-31	14	0.5-1.5	0.3-0.7	65-78	80-95
Rogaland	54-56	25-28	7-9	0.5-2	0.3-0.8	40-55	5-20

3. OVERVIEW OF NORWEGIAN PROSPECTING ON ANORTHOSITES

The first investigations of the anorthosites in Sogn for industrial use were made in 1917 by the renowned geologist V. M. Goldschmidt. Aluminium production based on acid leaching of anorthosite was his innovative idea, and the easily-soluble calcic Sogn anorthosites proved to be well suited for an acid process. Goldschmidt mapped parts of the large anorthosite massifs along Sognefjord in the period 1916-19. During WWII investigations were resumed, with sampling and core drilling, and a mine for that purpose was opened by Norsk Hydro in the northern part of Inner Sogn. Up to 400 men were employed and some 15,000 t of rock was produced before sabotage ended the work in 1945 (NRK 2006).

In the mid 1960s underground mining was started on altered white anorthosite near Gudvangen in Sogn and open-pit quarrying near Egersund in Rogaland. These localities have been in operation since then and the main uses have been as white road aggregate, filler, white concrete elements, mineral wool and abrasives in toothpaste and cleaning agents.

In 1975 the Norwegian aluminium companies Elkem AS and Årdal and Sunndal Verk AS were triggered by the formation of the International Bauxite Association to renew their interest in anorthosite as an alternative aluminium raw material. In the years 1976-1982 the joint venture company I/S Anortal carried out major geological investigations on the Sogn anorthosites, including core-drilling programs and larger processing experiments. The required 100 mill t of well soluble anorthosite with minor amounts of mafic minerals was located and a possible Norwegian alternative to imported bauxite was verified. The project was, however, terminated, as the concept was not found to be commercially compatible with existing bauxite-based alumina production. (Braaten 1991)

Late last century the Gudvangen anorthosite was the main target for companies that evaluated the rock as raw material in applications as water-cleaning agents and smelter-oven linings. Supplemental geological mapping and core drilling was then carried out (Wanvik 1999, 2000).

A recent, successful project has involved the geological mapping of local parts of the Rogaland anorthosite where phenocrysts of iridescent labradorite plagioclase have made the brown anorthosite attractive as a high-priced dimension stone. (Heldal and Lund 1995)

In a review of mineral deposits in Norwegian anorthosites the metallic minerals must also be given their proper position. In the RAP ilmenite ore bodies have been mined in various periods during more than 200 years, and the present production from the world-class Tellnes mine accounts for 7% of the world's total titanium mineral production. Smaller deposits of Fe-Ni-Cu-sulphides were also exploited at the end of the 19th century. In RAP more recent mapping has localized ilmenite bodies with interesting grades of apatite and vanadium (Schiellerup et al 2003).

4. OBSERVED ANORTHOSITE TYPES WITHIN THE SOGN PROVINCE

The geological mapping of the Sogn anorthosites revealed various anorthositic rocks: 4 different generations with a total of 9 subtypes have been suggested (Qvale 1982b):

1 a. Mottled anorthosite/leucogabbro
   b. Even-grained, banded leucogabbro
2 a. Even-/coarse-grained anorthosite
   b. Spotted anorthosite
   c. Dark red-brown even-grained anorthosite
   d. Grey medium-grained anorthosite/leucogabbro
3 a. Unevenly-grained dark violet or red anorthosite
   b. Unevenly-grained corona bearing leucogabbro
4. Pegmatitic anorthosite.

Of these, the types in category 2 are dominant in the Gudvangen area.

5. PHYSICAL AND CHEMICAL CHARACTERISTICS OF ANORTHOSITES IN RELATION TO INDUSTRIAL USES

Anorthosite is by definition an igneous rock consisting of 90-100% plagioclase feldspar. When the amount of mafic minerals exceeds 10 % the name leucogabbro or anorthositic gabbro (alternatively -norite) is commonly used, depending on the nature of the pyroxene. The plagioclase is of varying chemical composition in a solid solution series of its end members albite $NaAlSi_3O_8$ and anorthite $CaAl_2Si_2O_8$.

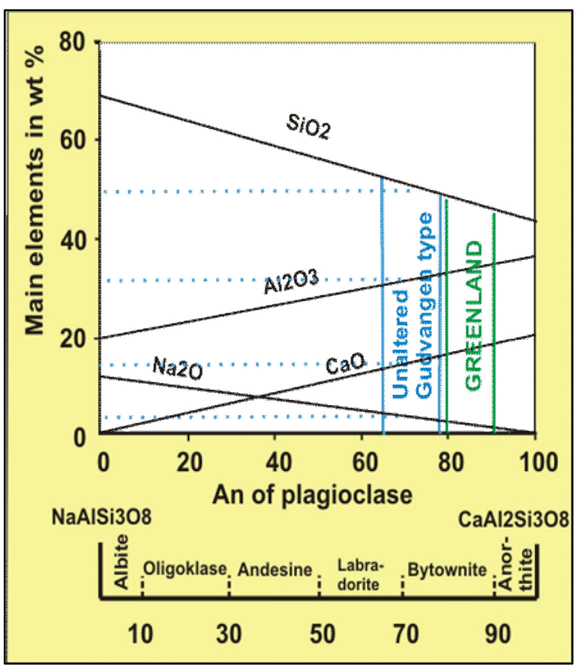

Fig. 3 Chemical composition of plagioclase

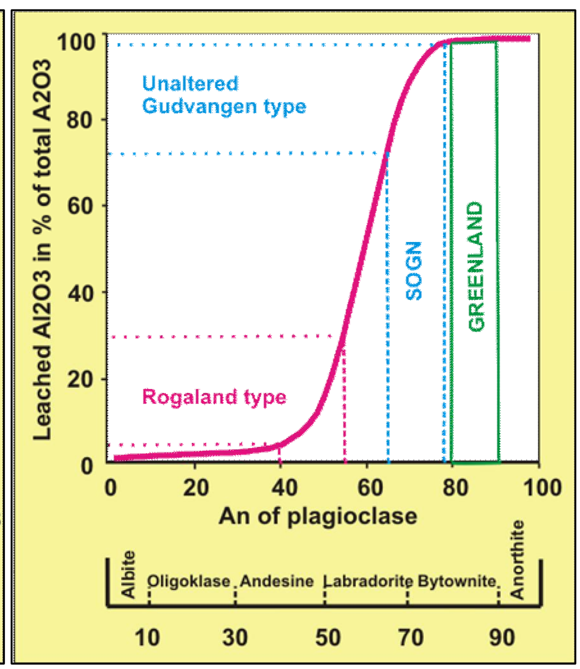

Fig. 4 Solubility of plagioclase

5.1 Solubility of anorthosite in mineral acids

One of the major potential uses of anorthosite is to extract the high content of aluminium. To manage this it is highly important that the rock is soluble in mineral acids: the solubility is found to vary drastically dependent on chemical composition, specifically An-content.

Already Goldschmidt during his surveys in Sogn in 1917 pointed out the importance of the An content for acid solubility and in 1924 he became aware that An_{50} was a rather critical level. During the Anortal-project Elkem in 1976 and thereafter NGU in 1979 tested many different plagioclase and anorthosite samples and a detailed solubility curve of plagioclase was established (figure 4).

The conclusion is that below An_{40}-An_{50} the plagioclase is hardly soluble at all, whereas above An_{70} there seems to be very high solubility. In the range between 50 and 70 the solubility rises sharply, corresponding with the Bøggild exsolution lamellae area. The crystallographic reason behind this nonlinear curve is found to be as follows:

Albite contains Al:Si in the ratio 1:3 and the acid attacking Al-O and Ca-O bonds is not able to penetrate below the surface of the mineral. At an Al:Si ratio of about 1.5 (An_{50}) the acid starts partially to make its way into the interior of the mineral grains. The Bøggild lamellae intergrowth gap from An_{45}-An_{60} with a mix of low-soluble and well-soluble lamellae seems thus to be the main reason why we see a gradual transition from non-soluble plagioclase to highly-soluble plagioclase in this area. (Ove Bøggild was a well-known Danish geologist with much field experience from Greenland). The dissolved lamellae have a resultant porous and amorphous silica residue structure. The dissolved ratio thus increases with increase in An and within the Huttenlocher lamellae intergrowth area (An_{67-95}) the lowest An lamellae will stabilize the residue structure. As soon as the An content exceeds this intergrowth area (around An_{95}) and the Al:Si ratio approaches 1:1 the SiO_2-tethraedra will also dissolve and the resulting silica residue will polymerize and precipitate as silica gel. The silica gel might give problems in an industrial process due to clogging of filters. On the other hand silica gel is a valuable product if its quality is good.

The anorthosites on Greenland, reported to be predominantly in the range of An_{60-90}, are then almost perfect in regard to an industrial process based on dissolving the rock. This high An content also means an especially high aluminium and calcium content - preferable if those two elements are wanted. In favour of the anorthosites of Greenland, it seems to be a fact that they are generally somewhat higher in aluminium and probably a little more soluble than the very best Norwegian ones in Sogn and Voss ï averaging An_{65-75} (fig. 4).

Figure 5 illustrates the influence leaching time and temperature have on the anorthosite. Both graphs are based on well-soluble Sogn anorthosite. High temperature is vital for good

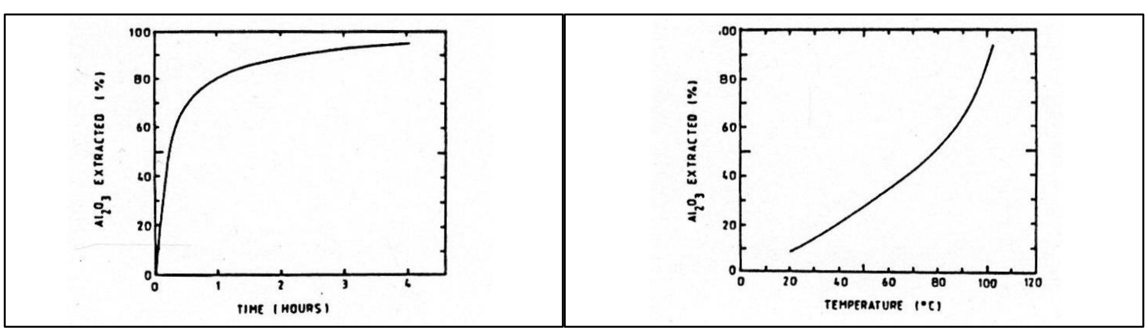

Fig. 3 Solubility in relation to time and temperature. (Gjelsvik 1980)

extraction. The rate of acid intrusion in easily soluble plagioclase (An_{65}) has been tested to be about 0.025mm/h with boiling 6N HCl, and thus the particle size of the Anortal process was defined to be 0.3-3mm in 24 hours leaching.

5.2 Alteration/saussuritization

In an evaluation of anorthosites for industrial uses the An content of the plagioclase is thus of high importance. Easily soluble high-calcium plagioclase can though be altered to non-soluble sodium-bearing plagioclase through metamorphic and tectonic processes. In this saussuritization process secondary low-An plagioclase replaces the primary grains and new minerals such as epidote, zoisite, chlorite and sericite are formed. The bulk chemistry is nearly unchanged but the plagioclase chemistry is greatly changed and the resulting rock is almost non-soluble. Fig. 6 gives a visual impression of the gradual decomposition of the larger plagioclase grains in a saussuritization process where first the rims along primary large grains are altered to fine grained low An plagioclase. Tensional bending of twinning lamellae is shown and some few large primary grains might resist until all primary grains are altered to a fine-grained white rock consisting mainly of albite/oligoclase, epidote/clinozoisite, chlorite and sericite/paragonite.

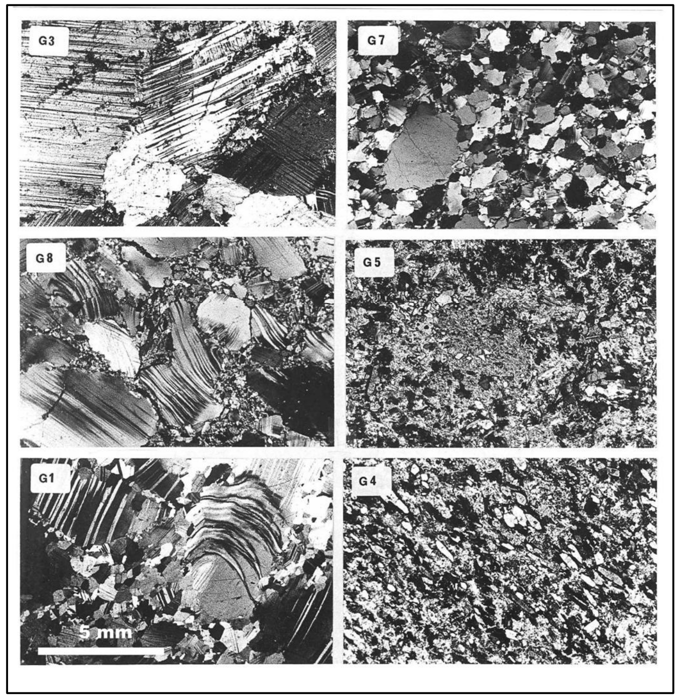

Fig. 4 Stages in alteration of bytownite to epodote-oligoclase in anorthosites Gudvangen-Stalheim area. (Bryhni et al, 1983)

5.2.1 <u>Honeycomb texture</u>

The first visible sign of a beginning alteration is sometimes clearly visible on weathered surfaces of anorthosite in the field, reflecting the first stage of alteration where only the rims along primary large grains are altered. When some of the plagioclase grains have an An content below 50 and others are in the soluble range then the non-soluble grains will protrude relative to the soluble ones. In parts of the Norwegian anorthosites in Sogn, grains of lower An plagioclase lie along the grain boundaries of larger soluble grains. This results in a honeycomb-like texture on weathered surfaces as illustrated in Fig 7. In an industrial leach-process it is the volume % of soluble and non-soluble

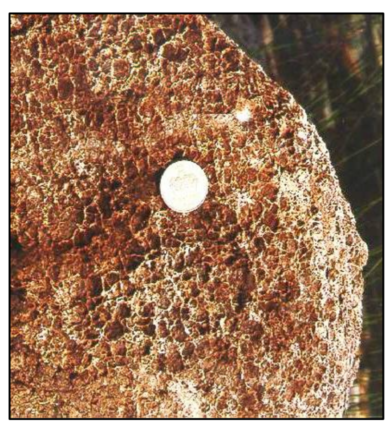

Fig. 5 Honeycomb texture on weathered anorthosite

plagioclase that affects the total solubility of a sample or a deposit, and when only rims around large grains are non- or weakly soluble then the average solubility will remain relatively high. This is also the case where alteration is concentrated on thin lines or zones.

5.2.2 Tectonic zones ï gneissification

When tectonic movements increase, the foliation increases and gradually gneissic zones will be produced. Saussuritization of the anorthosite then takes place and acid solubility is adversely affected. In the Sogn investigations some zones were found to be very local while others had a larger extent. In the drill cores of the Anortal project various such tectonic zones were intersected and the chemical analyses showed distinctly lowered solubility than the surrounding fresh anorthosites. The Anortal holes were drilled in predominantly fresh anorthosite, and the altered zones cut by drill holes were only some meters thick. The regional geological mapping of the Sogn anorthosites has, however, shown that the large anorthosite massifs are part of thrust sheets that have been moved relative to neighbouring rocks. The resulting alteration zone at the thrust base is found to be up to several hundred meters thick (figure 9). This altered zone has produced a white anorthosite with the typical non-soluble albitic plagioclase, epidote, clinozoisite and micas as dominant minerals (figure 6).

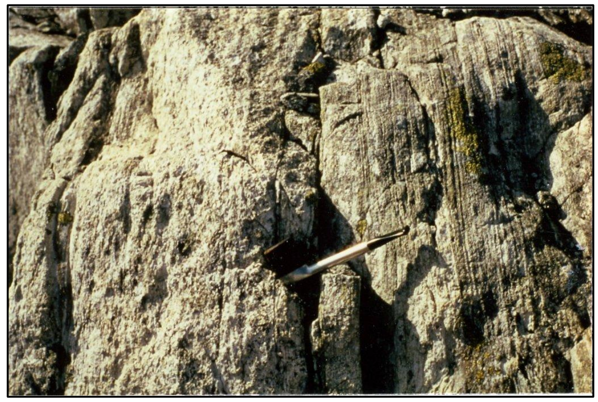

Fig. 6 Gneissified zone in Gudvangen anorthosite

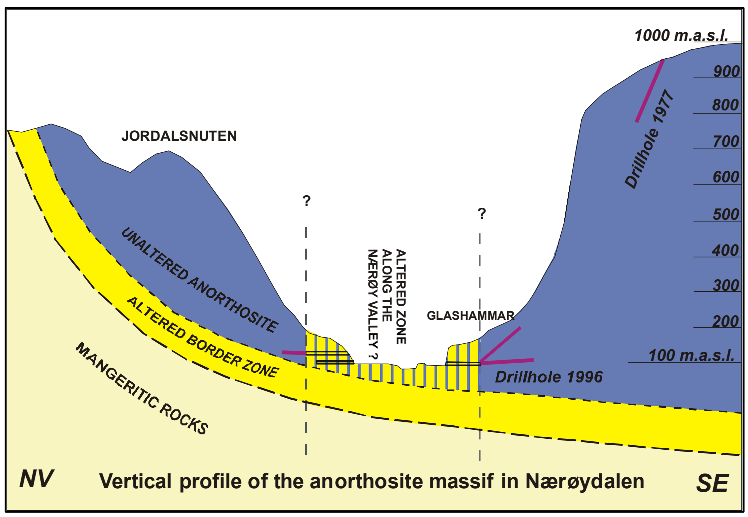

Fig. 7 Altered zones of the Gudvangen anorthosite

5.2.3 Hydrothermally altered zones

Mapping of the anorthosites in the Rogaland province has shown saussuritization due to hydrothermal processes. Along lineaments - zones of weakness where hydrothermal fluids have entered solidified anorthosite - the primary, dark-brown anorthosite has been altered to a white fine-grained rock composed of the typical zoisitic mineral assemblages.

These altered zones are mapped to be up to 15 km long and locally up to 700 m wide. These Rogaland zones have a predominantly NE-SW direction, but locally up to 100 m wide, with subordinate NW-SE zones occurring as shown in figure 10. These altered zones have given the anorthosite an improved mechanical quality and this rock is attractive, especially for export for white road aggregate. The whitest qualities are also used as fillers.

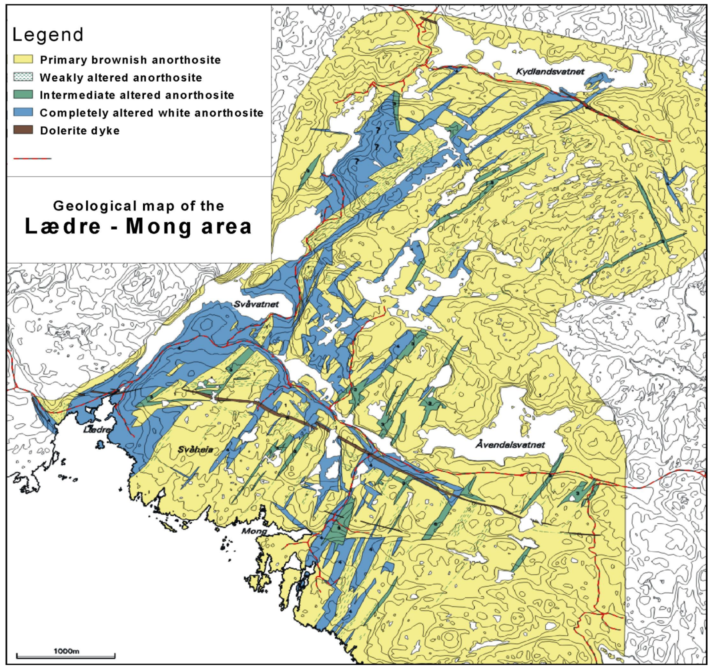

Fig. 8 Altered zones in the Rogaland anorthosite

In the Sogn anorthosites such hydrothermal alteration is not as easily recognisable, but there are clear indications that such alteration is partly responsible for some of the white, altered rock in the mining area in Nærøydalen. Observations of drill cores and mine mapping show that there must be a vertical alteration zone along the valley in addition to the horizontal, altered thrust zone at the base of the anorthosite massif (figure 9). The 500 m width of the alteration zone is similar to the thickness of the zones in Rogaland.

5.3 Contaminating minerals and rocks

Non-plagioclase minerals in primary anorthosite are predominantly dark minerals: ortho- and clinopyroxene, amphibole, garnet, olivine biotite, chlorite and epidote. In the good parts of the Gudvangen massif amphibole, biotite, chlorite and epidote are the major dark minerals. The mafic minerals are commonly scattered in spots and mottles/clusters, more or less elongated according to the foliation (figure 11 and 12).

Dikes of other rocks are very common in all the anorthositic areas in SAP. Most prominent are early gabbro and garnet-amphibolite dykes occurring as layers and lenses of varying

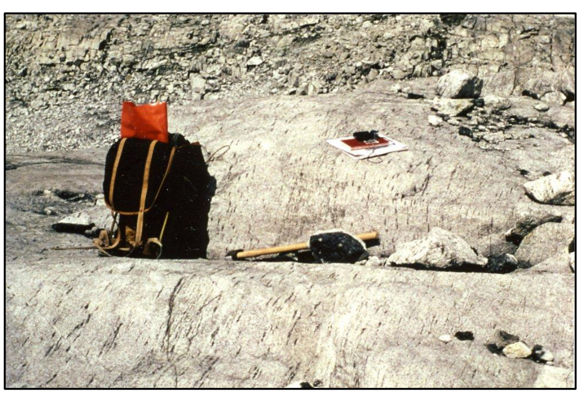

Fig. 11 Spotted anorthosite showing some foliation

Fig. 12 Mottles/clusters of dark minerals

thickness and frequency. These are a major negative factor against exploitation in many areas (figure 15).

Dioritic dikes are also present within the Sogn anorthosite. In some areas in the northern part of the province such dikes are dominant and make the areas uninteresting for industrial considerations, but in most areas diorites are only accessory and with a thickness of only 1-2 m they pose only minor contamination issues.

The mafic dikes are often folded and thus reveal that the anorthosite complexes are affected by pronounced internal folding. The huge thicknesses of up to 2000 m of the massifs are due to isoclinal repetitive folding of primary thinner anorthosite layers.

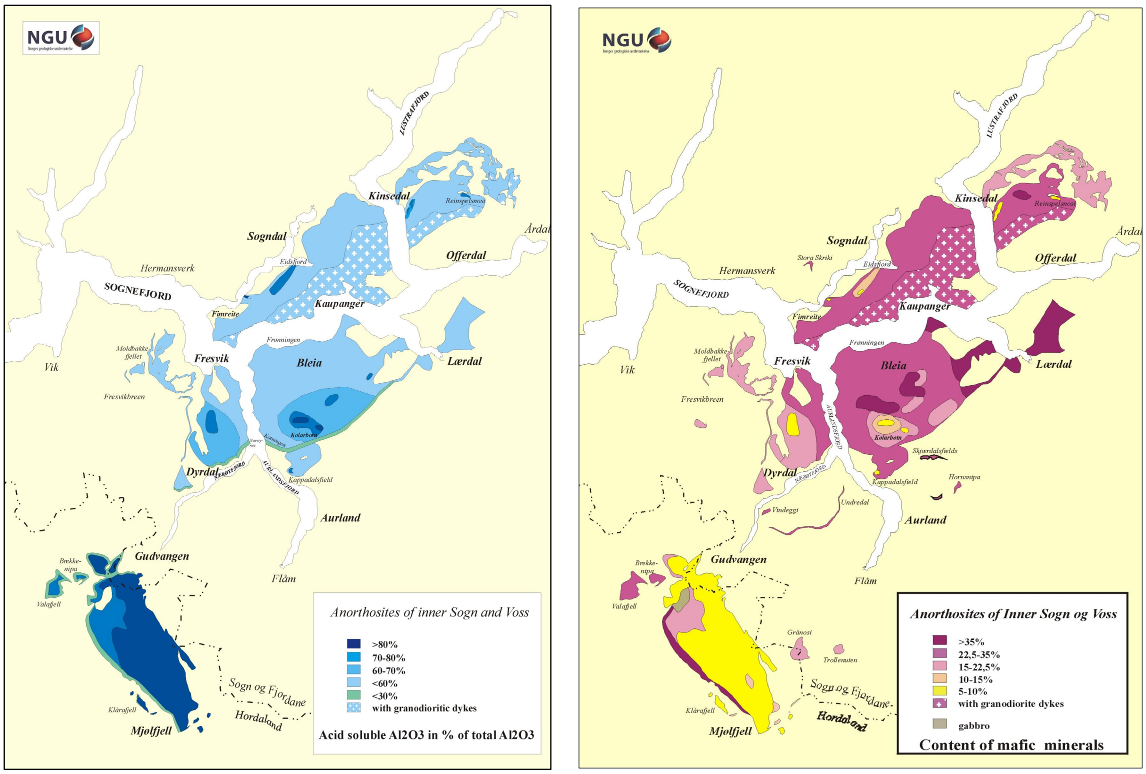

Fig. 9 Variations in solubility and content of dark minerals in the Sogn anorthosite province

5.4 Inclusions and colour of the anorthosite

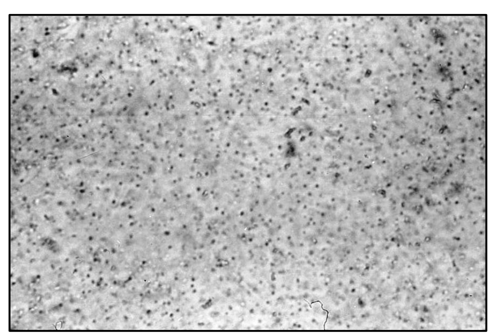

Fig. 10 Fe-oxides in primary plagioclase. Longest side 1.6 mm

The colour of the unaltered Sogn anorthosite may vary from almost white, through light grey to dark violet, brick-red and dark red-brown. The dark violet and reddish colours are due to sub-microscopic inclusions of Fe- and/or Fe-Ti-oxides exsolved from the original magmatic plagioclase. The colour does not necessarily reflect the An-content of the rock as brick-red Sogn types and heteroblastic violet types have low An, whereas dark red-brown anorthosites have the highest An. Various violet shades are a sign of excellent soluble quality in most of the better parts of the Sogn anorthosite. The Rogaland anorthosites are brownish to violet brownish-beige. When altered, anorthosite in general becomes white, no matter what the primary colour of the plagioclase is.

5.5 Grain-size and particle-size of processing

The majority of fresh Sogn anorthosites are medium- to coarse-grained with grain sizes of 2-5 mm. In processing this is advantageous, since the main leaching tests on a pilot scale have been with the 0.3-3.0 mm fraction, giving very good liberation of the separate mineral grains. One thing to be noted is however, that most of the primary plagioclase has many inclusions of small (< 0.02mm) euhedral epidote grains that follow the plagioclase product during processing. These epidotes are high in iron (8-12% Fe_2O_3) but they are not easily soluble in acids and do not noticeably affect the product in a leaching process.

The Rogaland anorthosite is coarse-grained (1-3 cm) with phenocrysts up to several centimetres across.

5.6 Solubility of other minerals

Depending upon which kind of industrial refining processes that is relevant in evaluating an anorthosite area, the solubility of the non-plagioclase minerals present might also be of relevance. If, for instance, the processing only includes magnetic separation before leaching, then contributions from remaining non-magnetic non-plagioclase minerals will be involved in the final leached product. The solubility of the non-plagioclase minerals varies and it seems that it is the more magnetically susceptible minerals such as biotite and chlorite that are soluble while the non-magnetic minerals as epidotes and zoisites are hardly soluble at all. With magnetic separation only minor amounts of Fe and Mg will then enter the solution.

6. FIELD PROCEDURES

In the Anortal project the main aim was to localize a deposit with a minimum volume of 100 million tons of easily soluble anorthosite for a 20-year mining period at 5 Mt/a. We then proceeded in three major steps.

The first necessity was to have an <u>acid-soluble anorthosite</u>, and in the Sogn anorthosite province several locations were satisfactory, but large areas were also not of the best soluble quality (figure 13). After initial surveys the most geologically and geographically suitable areas with easily soluble anorthosite were pinpointed close to Gudvangen (the bottom left body in figure 13).

The next step was to find areas with a <u>low content of non-plagioclase minerals</u>. These were mainly mafic minerals, easy to distinguish from the lighter plagioclase in the field; most areas had a higher content of mafic minerals than acceptable (figure 13). The Gudvangen massif proved to have large areas with an acceptable mafic content. During detailed fieldwork the anorthosite was subdivided into several subclasses dependent on content of dark minerals. In the best areas the content of dark minerals was below 1.5% and the average was below 3%.

The third step then was to exclude areas with too high a representation of dykes of other rocks. The dominating gabbroic and amphibolitic dikes occur partly in swarms and such areas are not attractive. In figure 15 is shown how the most dike-free area was chosen between areas with too many dikes. This area was thereafter investigated in detail, with mapping, sampling and a core drilling program. The required minimum100 Mt of good anorthosite for open-pit mining was then confirmed at two locations in the late 1970s. Today open-pit quarrying is not allowed in this area which, in the meantime, has become both a protected landscape area and a Word Heritage area.

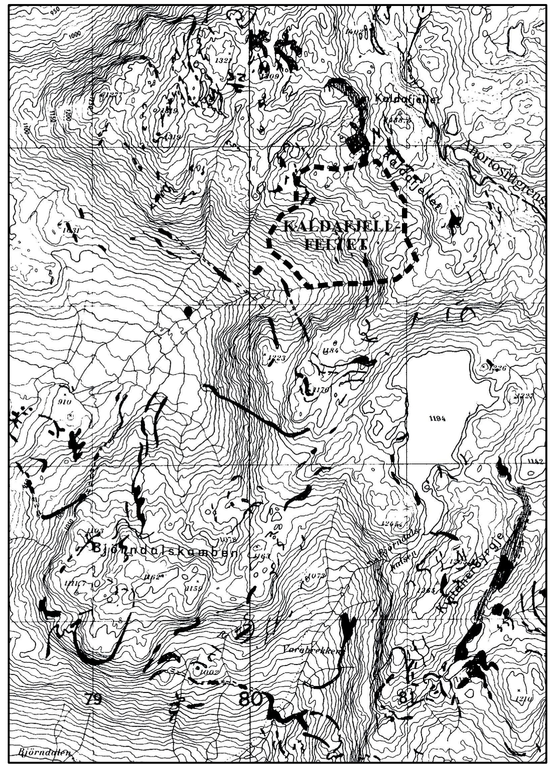

Fig. 11 Mafic dikes and target area in the Gudvangen massif

6.1 Sampling procedures

Feldspars are normally not very weathered in the Norwegian climate, and when doing reconnaissance and more detailed evaluations of the various zones and areas of the anorthosites an ordinary geological hammer or preferably a sledgehammer was used to take samples. The thinly weathered surface (some few millimetres in general) did not affect the chemical analyses of the samples noticeably, even though some surface removing most often was tried while preparing the samples. Using a sledge hammer made it also possible to beat off samples even on more rounded shaped surface areas. When sampling for representative chemical analyses during detailed mapping we collected several smaller samples from each local area and put them all into a bag ï some kilos in total. The size of each local area is somewhat dependent on the homogeneity of the anorthosite. In more regional initial mapping we collected mostly single samples to restrict the weight.

At an early stage a small portable core drilling unit was tested for sampling, but the feldspar proved too hard for this machine to have any adequate effect in the field. New equipment today (30 years later) might be noticeably better, but sledge-hammer sampling will normally give more flexibility and much higher speed in a sampling situation. For larger samples for processing tests dynamite was used and the diamond drilling programs were executed with heavy equipment giving 32 mm cores. The lengths of the holes were 100 to 250 m In the Anortal project a total of 3000 m were drilled. In order to do good detailed mapping topographical maps were constructed at 1:2000 as a supplement to available topographic maps and aerial photos. One might mention that this was long before GPS became available.

6.2 Techniques for verifying plagioclase quality in the field

6.2.1 Colouring methods

During the Anortal project various field methods for distinguishing plagioclase variations were tested. Of these two different colouring techniques was examined, using Methylene yellow and Rhodisonate. Both methods required use of acids to leach rock surface in the field and because the colour intensities proved to be rather unreliable in the region An_{50}-An_{80}, none of them were found to be practical.

6.2.2 Portable field XRF analyzer

Far more successful was the use of a portable XRF analyzer (M853B, Nuclear Enterprises) to determine the An content in the field by measuring the calcium content. Correlations between field measurements and laboratory-checked analyses were good and gave good indications of the An content of fresh anorthosite. Some field parameters, such as humidity, unevenness and weathering of measured surface might give somewhat inconsistent values and for better reliability a hand-portable crusher and agate mortar was used during part of the fieldwork. All in all, the instrument proved to be a good tool in distinguishing between anorthosites of different primary chemistry

Hand-held XRF analysers have improved much in the 30-year time span since then and I presume several of these are more efficient than the one we used in the 1980s.

7. PROCEDURES FOR CHEMICAL ANALYSES AND ACID SOLUBILITY

Major-element laboratory analyses have been done by ordinary laboratory XRF. To detect acid solubility a standard procedure has been followed. In short it is as follows:

> The sample is crushed and briefly milled. 10 g of the fraction 200-270 mesh is then leached with 40 ml 6N HCl for 2 hours in a glass flask while boiling (ca. 10 min, 108-109°C). The residue is separated out by filtering and washed with distilled water until free from acid. Both residuum and leach are analysed for major elements. A more classical method (wet chemistry) was used on leach, while XRF on residuum and initial material.

The solubility curve in Fig. 4 is based on this procedure.

Today a quicker procedure might be handy to test for solubility, and in recent analyses the following has been used in order to find just the total solubility of the samples:

> 1.000g, dissolved in 20 ml HCL (1:1), 2 hours on boiling-point water-bath, then 3-5 min boiling on hotplate. Filtered on weighed 8micron membrane filter, dried 24 hours at 20°C.

This procedure is based on a standard procedure for carbonates and seems to give results that are around 30 % lower in solubility than the old standard anorthosite method. A full comparative solubility curve has not been established as this has so far only been regarded as a quick method to find relative differences of various samples.

8. INDUSTRIAL PROCESSING AND QUALITY SPECIFICATIONS

Anorthosite is primarily composed of plagioclase and thus has some of the same industrial uses as commercial uses of plagioclase feldspars from pegmatites. Pegmatite feldspars are mainly albitic, and thus have higher sodium and lower calcium contents than anorthosites in general and Greenlandic anorthosites especially.

The calcic anorthosites of Greenland are in the similar category as the Sogn anorthosites and thus have mainly the same potential end uses. A short overview of main uses and related industrial processing are given ï summarized in tables 3 and 4.

The high aluminium content of the Sogn (and Greenland) anorthosites is the major advantage compared to most anorthosite bodies worldwide: their possible use as an alternative raw material in aluminium production has been evaluated and tested in various processes.

The Norwegian process developments for this purpose have been based on leaching with various strong mineral acids, such as hydrochloric, sulphuric or nitric. In the Anortal-project (Braaten 91) HCl was found to be most suitable and the pilot-scale processing done by the Institute of Energy (IFE) proved to be very successful with a total of 4 t of good-quality aluminium oxide produced (figure 16) (Gjelsvik 1980). The process was, however, not commercially competitive with ordinary bauxite-based alumina production.

A later development at the same institute (Andresen 06) based on natural-gas introduced nitric acid (HNO_3) as dissolvent and added CO_2 and ammonia (NH_3) as reacting agents in the process to yield additional attractive products such as calcium carbonate, silica-residue and ammonium nitrate (figure 17). Surplus CO_2 from a gas power plant is bound with calcium from the anorthosite to form calcium carbonate (PCC). Nitric acid is borrowed from natural-gas based fertilizer production.

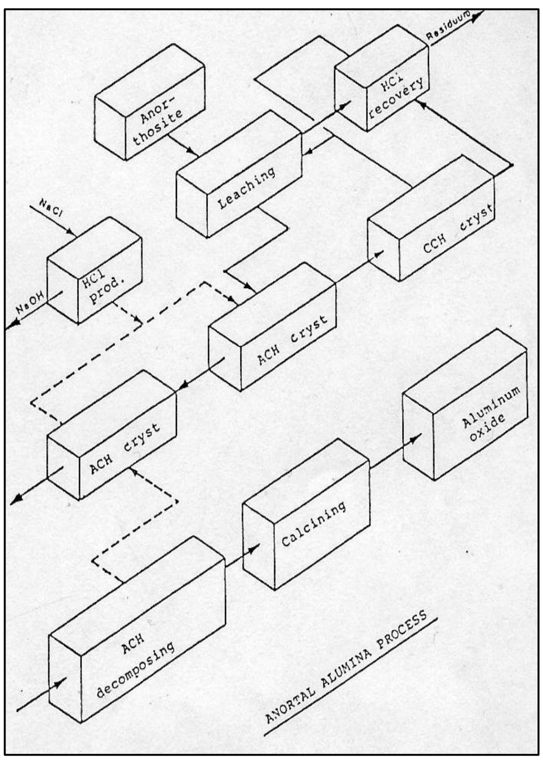

Fig. 12 Anortal process flow sheet

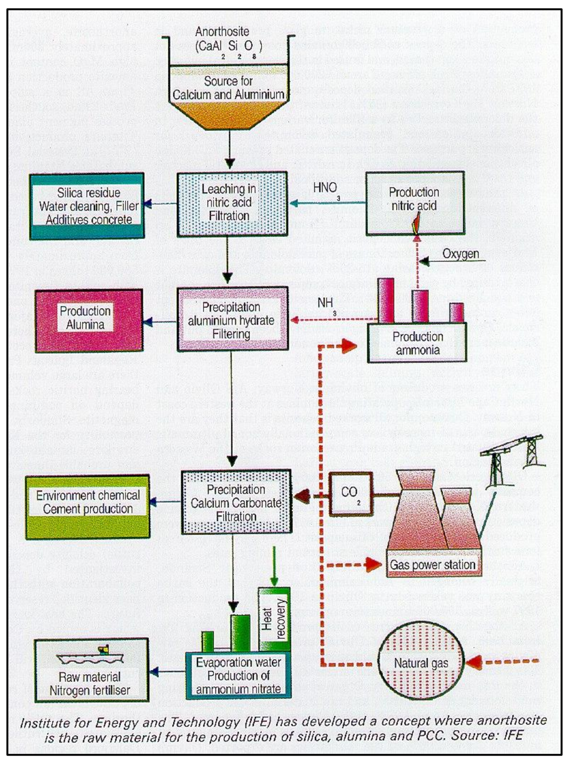

Fig. 13 Modified process incorporating CO_2

Attractive products such as calcium carbonate, silica-residue and ammonium nitrate are then produced (figure 17, table 2), making a close to full use of all the components of the anorthosite. So far this environmentally well-profiled alternative has proven technically workable but important process and product developments still remain to properly assess product qualities, refinement and cost of operations and resulting economical calculations. The concept is at present in need of money/investors. The size and complexity of the concept is somewhat of a deterrent to established industrial companies, but potential income from high-value products such as PCC and precipitated silica in addition to the alumina gives a solid basis for future expectations of commercial realization of this CO_2-integrated concept, a future also dependent on market prices of carbon credits.

Table 2 Consumed and produced quantities of a CO_2-integrated concept, *handling CO_2 emissions from a 3TWh gas power plant*

	Anorthosite	**Silica**	**NH_4NO_3** (minimum)	**Al_2O_3**	**$CaCO_3$**	**CO_2** (2.5-3 TWh)
Tons/year	8 000 000	4 000 000	2 800 000	2 000 000	2 000 000	1 000 000

A third acid-leaching process that has been carefully tested in Norway (and abroad) is an alternative HCl-process with the mission of producing a polymeric aluminium-based coagulant for cleaning of drinking and waste water. This project has also been proved technically viable but the developers did not fully make it to commercial success.

Alkaline leaching of the anorthosite also allows extraction of the aluminium component, but such processes are more costly and more energy-intensive and have not been further considered in Norway.

Leach processing gives a highly porous silica residue as one of the products, and this has proved to have several potential applications (table 4). Some of these have been tentatively tested and evaluated on material from the above-mentioned processes. All the leaching processes require a soluble calcic anorthosite and low content of mafic minerals is advantageous.

Processes that include some melting of the raw material have been tested for several uses. Of these the successful application as a major raw material in mineral-wool production is of great importance for the Sogn mine in Gudvangen, at present having nine European Rockwool factories as customers. White Rogaland anorthosite has, for several years, been sold to the ceramics industry for tile and sanitary porcelain production.

Two other possible applications (developed in Norway) in the metallurgical arena that have been promising, but not so far been commercialized are:

- Use of the Sogn anorthosite as a raw material for a new refractory product designed as a sealant for aluminium electrolytic cells in the aluminium industry.
- As raw material in an alternative new direct electrical melting method of producing both aluminium and solar-grade silicon.

Concerning other uses of the Norwegian anorthosites they can be labelled under physical processing, as in sawing and polishing to dimension stones, crushing for white road aggregates and concrete elements and, with some additional grinding, to the former uses in toothpaste and scouring powder.

Table 3 Important characterisation criteria for anorthosite in different applications

Use	Acid solubility	Al	Fe	Ca	Na	LOI	Other	Quantity need
Al-production	high	high	low					large
Al + CO_2-free natural gas power plant	high	high	low					large
Water cleaning	high	high	low				not quartz	medium
Si + Al-production by electrolysis		high	low				high, low B and K	large
Refractive		high	low	high		low	not quartz	small
Ceramics			low			low		medium
Mineral wool		high		high			low Si	medium
Aggregate							whiteness, mechanical properties	medium/large
Glass-fibre					low			small/medium
Dimension stone							fracturing, block size	small

Table 4 Commercial and potential uses of anortosite. *Norwegian operative or tested uses in italics.*

Processing	Products	Uses	Specifics
Physical. (dry or wet mineral processing)	Plagioclase grains with crystal structure intact (White altered variety most attractive)	Aggregates	***Light coloured road surfaces, gardens***
		Building materials	***Concrete elements, dimension stone, industrial floors***
		Abrasives	***Scouring powder, toothpaste***, sand blasting
		Fillers, Extenders, coatings	Paint, plastics, rubber
Chemical (acid or alkaline leaching)	Aluminium chlorides ***Aluminium oxide (alumina)*** Aluminium sulphate (alum) ***Calcium carbonate*** Calcium nitrate Calcium silicate ***Ammonium nitrate*** Silica gels and sols Sodium silicates Sodium carbonate	Aluminium metal	
		Flocculent	***Water and waste water treatment***
		Flocculent/sizing	Paper manufacture
		Binder	Asphalt
		Catalyst	Organic reactions
			Alumina speciality products
			Cellulose insulation
			Cement components
			Cosmetics and Pharmaceuticals
			Food processing
			Nitrogen fertiliser
			Speciality metallurgical uses
			Synthetic wollastonite and zeolite
	Silica residue	Fillers and extenders	Polyester and epoxy resins, Polyurethane varnishes
		Coating	White enamel
		Absorbent	Kitty litter
		Silicon production	
			Cement additive
Melting	Full or partial melting of plagioclase grains	Ceramics	***Floor and wall tiles***, electrical porcelain, bioceramics, ceramic glazes
		Glass fibre	
		Mineral Wool	***Rockwool***
		Welding fluxes	
		Al-production cells	***Cryolite bath insulation***
Direct reduction	***Al-Si-alloys, Al- and Si-metal.***		

9. SPECIAL ASPECTS RELEVANT TO ANORTHOSITE PROSPECTING IN GREEENLAND

The Norwegian attempts to commercialize anorthosite as an aluminum raw material have not been successful so far, and GEUS is interested in the reasons for this.

The operations during WWII, when a full scale mine and transport facilities were constructed, had as background the special conditions with wartime alternative supply to overseas raw material. The economic considerations were thus extraordinary.

The Anortal project was based on showing the then newly-formed International Bauxite Association that an alternative aluminum raw material was available if bauxite prices escalated. This prevention task proved successful as 4 t of good-quality aluminium oxide was produced, but without hoped-for cheap North Sea gas the oxide produced by the Anortal process was not economically compatible with the traditional bauxite-based process.

In the later modified process with CO_2 as a reactant, a close to total utilization of all the major elements of the anorthosite is though envisioned, giving definitely better possibilities for economic success. The process developments in such an advanced process are however of a larger scale, and important developments and tests are still needed to get a fuller view of the feasibility and contributions of the various processing steps and products in a total economic evaluation. The market possibilities of the non-aluminium products such as SiO_2, $CaCO_3$ and NH_4NO_3 are much dependent on their final purity and this remains to be developed before a full-scale economic feasibility study is possible.

The calcic (An_{60-90}) (and mainly Achaean) anorthosites in Greenland are more easily acid soluble and higher in aluminium than the best Norwegian ones and this might make room for somewhat better products and more potent economics than we might envision with the Sogn anorthosite. Levels of energy consumption in the new integrated process are much dependent on further process developments, but potential moderately-priced Greenland electric power would be an important advantage. With relative proximity to the American and European markets the Greenland anorthosites might be a very interesting prospect.

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