DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2011/144

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Compositional variation and potential use as raw material in aluminium production

Christian Knudsen, Jan Wanvik & Henrik Svahnberg

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G E U S

Summary

Anorthosite is an almost monomineralic rock type consisting of more than 90 % plagioclase. Plagioclase is an aluminium rich mineral and experiments conducted in Norway over most of the last century have proved that it is technically possible to use anorthite as a raw material in the production of aluminium metal. Because the solubility of the anorthosite increases with the calcium content (anorthite content) in the plagioclase (% An). The An% is very important when evaluating the quality of the anorthosite as a raw material for aluminium production.

This report provides an overview of the whole rock and mineral chemical composition of 12 anorthosite complexes in Greenland with focus on the chemical composition of the plagioclase. It is found that all the Greenlandic anorthosites belong to the calcic Archaean type but that the chemistry varies both among the different complexes and within the complexes. Within the samples analysed there is a considerable variation in the plagioclase composition which often is caused by recrystallization during metamorphism.

The anorthosite of the Fiskenæsset area both has the highest CaO content in bulk rock and also contains the most calcic plagioclase found in Greenland but the anorthosites from Nordlandet also have a bulk rock composition suggesting the presence of highly calcic plagioclase in these rocks as well. Almost all of the Greenlandic anorthosites are more calcic than their Norwegian counterparts.

The Paleoproterozoic anorthosite bodies in the Inner Sogn-Voss area of Western Norway by the Sognefjord have a labradorite-bytownite plagioclase composition with anorthite content of 60-78%.

The high aluminium content of the large anorthosite bodies by the Sognefjord has made them potential alternative sources for the aluminium industry. In several phases during the last 90 years major Norwegian companies have done extensive geological and process technological investigations with this aim. Aluminium metal production based on anorthosite is still regarded as an interesting industrial possibility combined with generating by-products consisting of calcium carbonate, amorphous silica and nitrate fertiliser. The process further more attracts attention because it is possible to remove CO_2 from e.g. power production by this method.

Content

Introduction

This report is prepared by GEUS in cooperation with Bureau of Minerals and Petroleum, Nuuk.

Objectives

Anorthosite is by definition an igneous rock consisting of more than 90 % plagioclase (Streckeisen, 1976). Plagioclase is an aluminium-rich mineral, and when the rock is almost monomineralic, the aluminium content in the rock is high. This property makes anorthosite interesting as a possible source for aluminium metal production, because calcium rich anorthosite is acid soluble e.g. in nitric acid. The acid solubility of anorthosite increases with the Ca (anorthite) content in the plagioclase.

Anorthosites occur as major and minor bodies in many parts of Greenland and this report constitute a brief description of the major anorthosite occurrences in Greenland with emphasis on the anorthite contents in the plagioclase. The report is based on available published data together with new whole-rock and microprobe analytical data on archived and new samples.

Apart from this, the report aims at summarising the experience from testing anorthosite as raw material for aluminium production in Norway.

Anorthosite complexes are also interesting in context of mineralisation’s of platinum group elements, chromite and ilmenite. These aspects will be described in other reports from GEUS.

Background

Since 1903 anorthosite has been thought of as an alternative to bauxite as a source for aluminium in Norway and the first investigations of the anorthosites in Sogn for industrial use were made in 1917 by V.M. Goldschmidt (Goldschmidt, 1917). Aluminium production based on acid leaching of anorthosite was his innovative idea.

In 1975 the Norwegian aluminium companies Elkem AS and Årdal and Sunndal Verk AS formed a joint venture company I/S Anortal. They succeeded in producing as much as 4 tons of alumina. However, the project was discontinued in 1987 because the energy consumption in extracting the alumina was substantially higher than in the conventional "Bayer process" and because the investment needed was too large.

The main finding in the Anortal project was that anorthosite with CaO/Na_2O ratio of more than 0,65 could be dissolved or leached using strong acid at 90^o C, leaving an amorphous residue of siliceous material. Further, it was found, that the degree of leaching increases with the Ca content in the plagioclase.

Ca. 10 years after the Anortal project was closed, a new concept was suggested by Institutt for Energiteknikk (IFE). The idea in this concept was to use not only the alumina for aluminium production, but:

- The silica residue as micro silica with many industrial and environmental applications
- The calcium for precipitation of CO_2 and production of precipitated calcium carbonate ($CaCO_3$) used e.g. as a filler in paper and thereby also serve as a sink of CO_2.
- The acid used in this concept would be nitric acid and nitric fertiliser would be a by-product.

Apart from these potential applications, anorthosite can be used e.g. as aggregates (light-weight, tough) and as dimension stone.

Anorthosite geology

Anorthosites can be divided into a number of types and Ashwal (1993) has established 6 basic types:

1. Archaean (calcic) anorthosite
2. Proterozoic (massif-type) anorthosite
3. Anorthosites in layered mafic complexes
4. Anorthosites of oceanic settings
5. Anorthosite inclusions in other igneous rocks
6. Extraterrestrial anorthosites

As indicated, the Archaean anorthosites are calcic, meaning that they have a high Ca contents in their plagioclase and often fall in the "bytownite" field ($An_{75\text{-}90}$). This feature distinguishes the Archaean anorthosites from e.g. the Proterozoic Massif type which fall in the range $An_{35\text{-}60}$ (Ashwal, 1993). So far only the Archaean types of anorthosites have been described from Greenland.

The Archaean anorthosites are generally deformed and metamorphosed to an extent where their genetic relationships to surrounding lithologies can be difficult to reveal. However, e.g. in the Fiskenæsset Complex, primary textures and relations are locally preserved, and it can be seen that the anorthosites are part of large mafic intrusions of basaltic composition and formed as cumulates by crystal fractionation. In these igneous complexes the content of mafic minerals is variable and the anorthosites often occur together with leucogabbro, gabbro and ultramafic rocks. The primary relationship to the surrounding rocks is often obscured by tectonic activity or intrusive contacts to younger granitoids. However, where primary relations are preserved anorthosite complexes are intruded into supracrustal rocks/greenstone belts (Ashwal, 1993).

Methods

Microprobe analysis was performed using the JEOL JXA-8200 Superprobe at Institute of Geography and Geology, Copenhagen University.

The instrument has 5 wavelength dispersive spectrometers, and the acceleration voltage was set to 25 kV and the beam current to 25 nA.

Anorthosite complexes in Greenland

Anorthosite is known from all Precambrian basement areas in Greenland and the most prominent complexes are shown on Figure 1. The anorthosites are most abundant in the Archaean gneisses both in south-western and south-eastern Greenland where they generally occur as concordant layers and trains of inclusions.

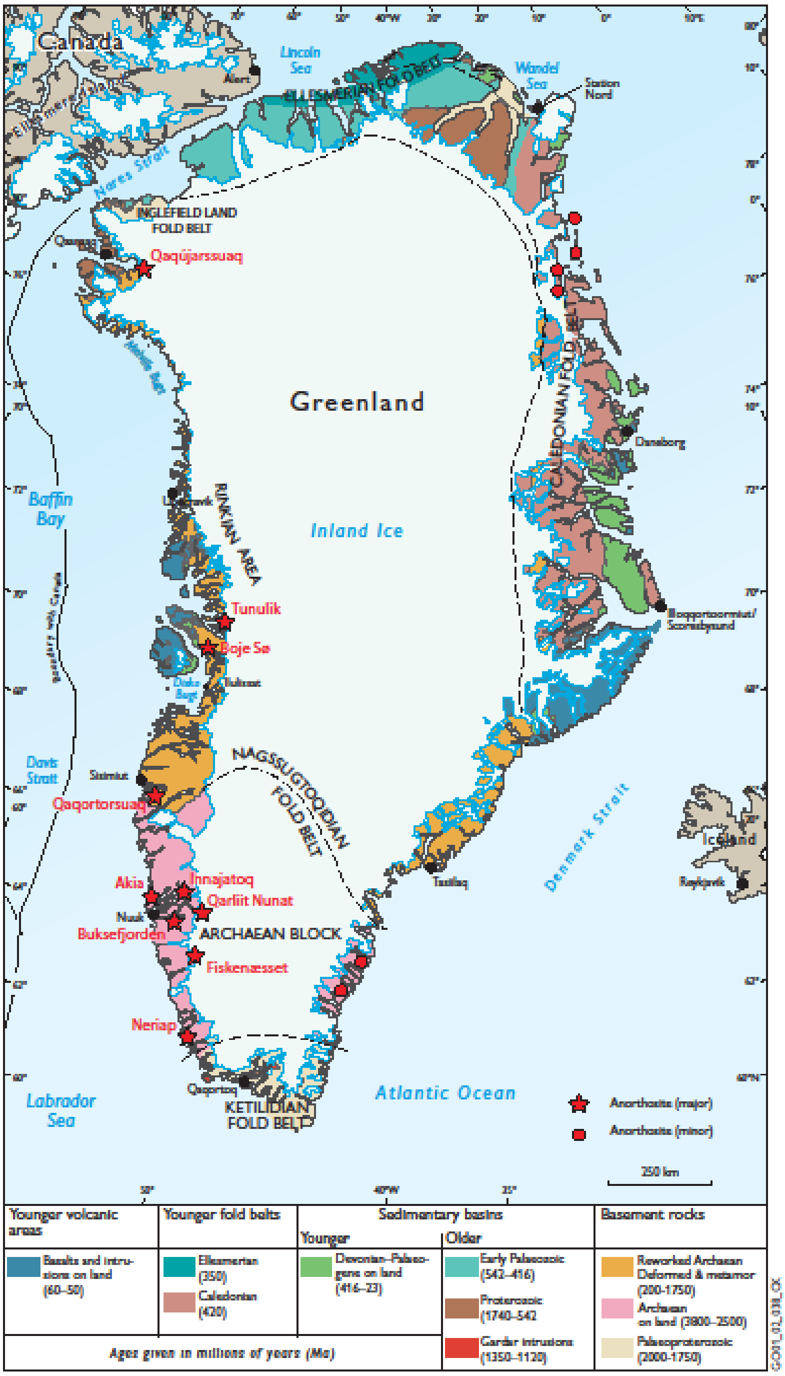


Figure 1

Major anorthosite complexes in Greenland.

The distinctive weathering pattern of anorthosites can be utilized when mapping the regional structure in areas where they occur and they can be traced in continuous outcrop for as much as 25 km along strike.

In the Fiskenæsset region, anorthosite form as much as 5 % of the total outcrop area. The anorthosites have been deformed and metamorphosed, and only locally primary igneous textures can be observed.

Qaqujârssuaq Anorthosite

The Qaqujârssuaq anorthosite – the largest single anorthosite mass in Greenland – covers the northern *ca.* 100 km^2 of Smithson Bjerge and has an unknown extent under the Inland Ice (Dawes, 2006). It represents a *ca.* 500 m thick succession exposed in an overturned antiform.

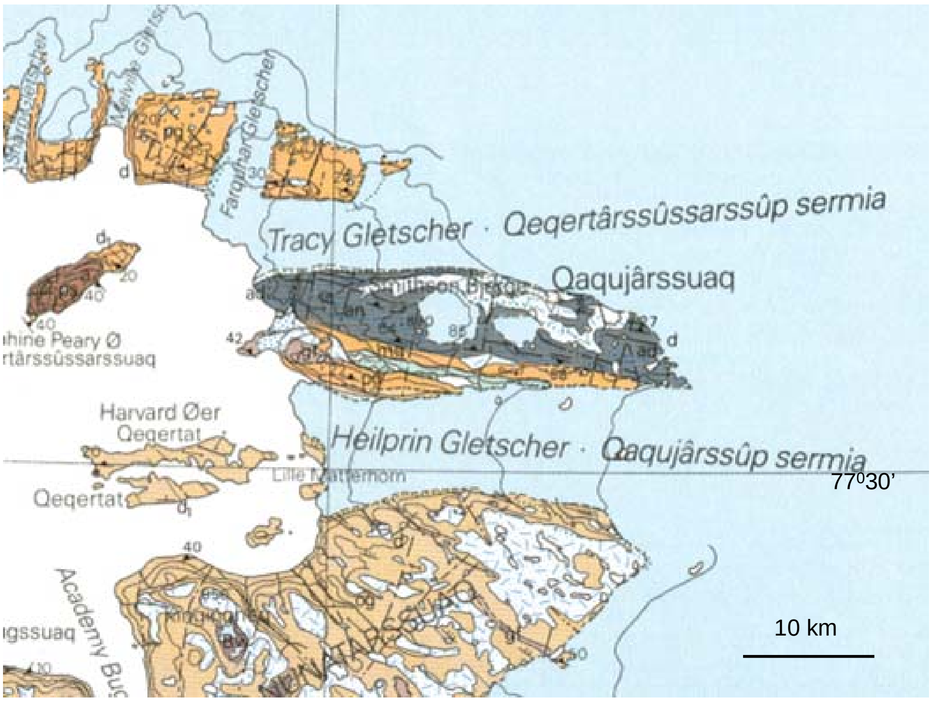


Figure 2 Location of the Qaqujârssuaq anorthosite (grey). (Dawes, 1991).

The Qaqujârssuaq anorthosite body was first described by Dawes (1972). It is strongly deformed and all internal structures, including mafic foliation, schlieren and banding are parallel to the exposed contact to the basement (Nutman, 1984 & Dawes, 2006). Only within local low-strain areas igneous features are preserved and these include planar layering, plagioclase and pyroxene megacrysts, and sporadic graded bedding. There is appreciable lithological variation within the body due the highly variable proportion of anorthosite to leucogabbro. Nutman (1984) was able to map three main E–W-trending zones on this basis. Large parts of the anorthosite contain little or no leucogabbro whereas elsewhere leucogabbro in 25–50 cm thick layers (and thicker), is commonly interspersed with anorthosite. Several lithological types of leucogabbro occur ranging from strongly banded to equigranular and megacrystic pyroxene leucogabbro, including “tennis ball” textures and brecciated types. The plagioclase is calcic (Table 1), ferromagnesian minerals are predominantly hornblende + clinopyroxene ± orthopyroxene; garnet occurs locally (Nutman, 1984).

Figure 3 Qaqujârssuaq anorthosite (an) with the typical light weathering colour in contact to orthogneiss (og) below which the brown coloured paragneiss (pg) is seen with granite sheets (gf). Smithson Bjerge (Dawes, 2006). Photo: Bjørn Thomassen

The exposed contact to the paragneiss (pg on Figure 3) is a sheeted zone with thin anorthosite units. The anorthosite is considered to have been emplaced *c.* 2700 million years ago as a liquid-crystal mixture and composed of *c*. 90% anorthosite, with less than 10% leucogabbro and 1% gabbro (Nutman 1984).

Table 1 Whole rock composition of anorthosite samples from Qaqujârssuaq (Nutman, 1984)

Sample	**235644**	**235613**		**CIPW norm**	**235644**	**235613**
SiO_2	47,95	49,03		Calculated Ca/(Ca+Na) in plagioclase	81,2	73,4
TiO_2	0,05	0,14				
Al_2O_3	30,92	28,89		Quartz	0,6	0
FeO	0,68	1,71		Plagioclase	93	90,3
MnO	0,01	0,03		Orthoclase	0,5	0,8
MgO	1,47	2,02		Diopside	2	2,8
CaO	15,69	14,07		Hypersthene	3,8	3,9
Na_2O	1,95	2,69		Olivine	0	1,7
K_2O	0,08	0,13		Ilmenite	0,1	0,3
LOI	0,56	0,88		Magnetite	0,1	0,3
Sum	99,36	99,59				

Tunulik Anorthosite

The Tunulik anorthosite was discovered by T.C.R. Pulvertaft in 1965 (Pulvertaft, 1973) and later mapped by Morten Andersen in 1978 and 79 (Andersen & Pulvertaft, 1986).

The Tunulik anorthosite (Figure 4) consist the main occurrence of anorthosite in the Umanaq area. It mainly occurs as a sheet consisting of foliated anorthosite and leucogabbro blocks ca. 1 to 3 m in size in a biotite gneiss matrix that wraps around the anorthosite blocks. The sheet is up to 300 m thick.

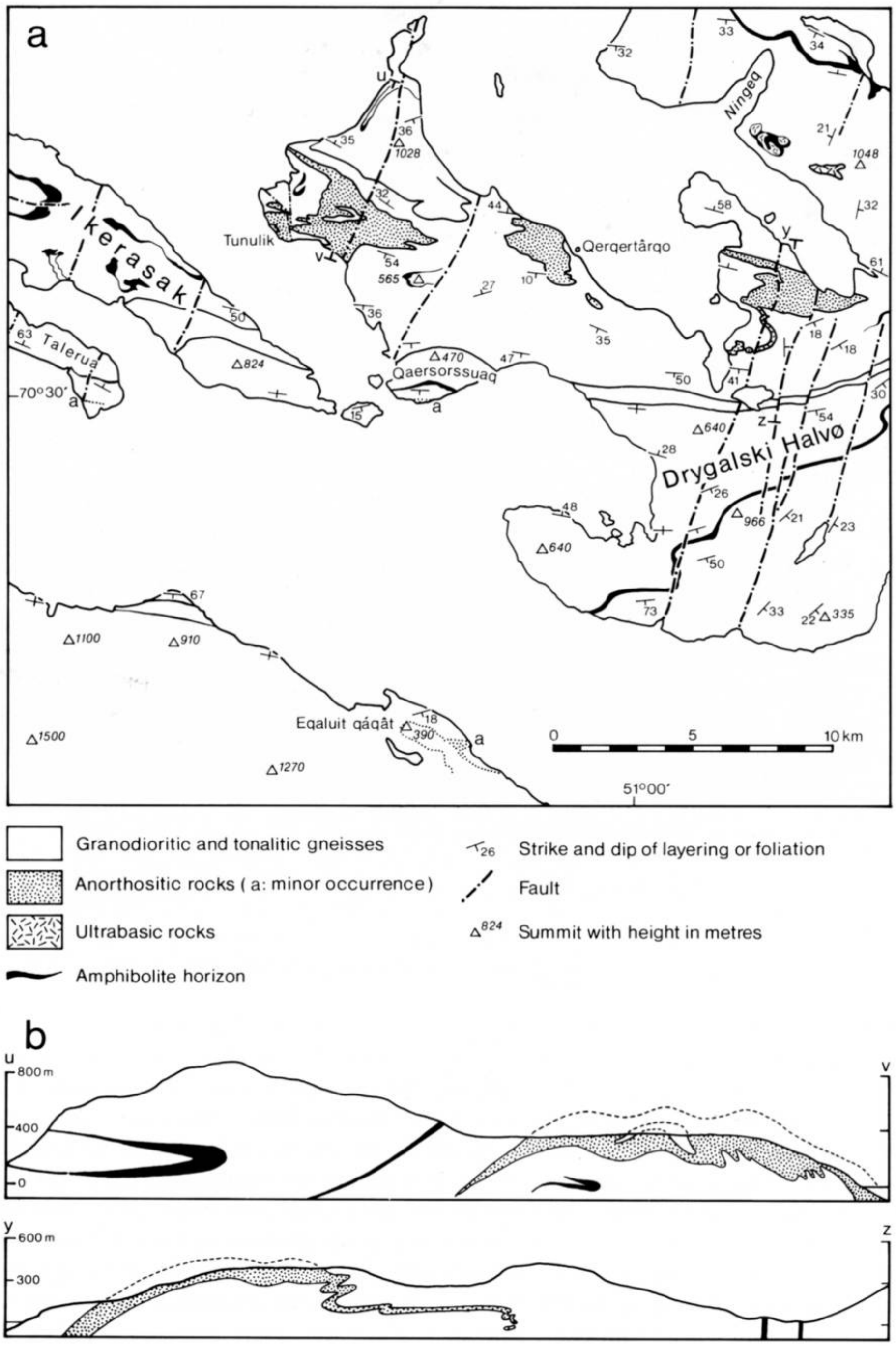


Figure 4

Location and structure of the Tunulik anorthosite from Andersen & Pulvertaft (1986).

The texture is medium-grained, granular without the igneous textures described elsewhere in Greenland. Under the petrographic microscope it can be seen that the texture is granoblastic and that the larger grains are zoned. The anorthite content of the plagioclase has been measured optically (Andersen & Pulvertaft, 1986) and varies from An_{82} to An_{68} with the lowest values found in the crystal rims.

Table 2 Tunulik anorthosite chemistry (Andersen & Pulvertaft, 1986)

	83625	**83631**	**246804**	**246849**	**83649**	**Mean**
SiO2	49,55	49,55	50,12	52,56	53,01	51,0
TiO2	0,08	0,1	0,09	0,07	0,01	0,1
Al2O3	29,45	28,89	29,49	27,77	28,68	28,9
Fe2O3	0,46	0,16	0,29	0,18	0,16	0,3
FeO	1,12	1,41	1,11	1,08	0,17	1,0
MnO	0,02	0,03	0,02	0,02	0,01	0,0
MgO	0,82	0,77	0,58	0,66	0,09	0,6
CaO	13,03	13,52	13,43	12,57	11,9	12,9
Na2O	3,25	3,22	3,37	3,44	4,21	3,5
K2O	0,52	0,36	0,81	0,37	0,38	0,5
LOI	0,7	0,62	0,83	0,26	0,39	0,6
Sum	99,01	98,64	100,15	98,99	99,02	99,2
CIPW norm						
% An in plag.	69,3	69	70,8	65,8	60,6	67,1
% Plagioclase	92,6	91,9	88,1	89,5	95,2	91,5

Apart from the Tunulik anorthosite there are several small occurrences of anorthosite in the Umanaq area and anorthosite can be traced south to the Nuussuaq peninsula.

Boye Sø Anorthosite

The Boye Sø anorthosite complex form a ca. 25 km^2 large body consisting of anorthosite, leucogabbro, gabbro and ultrabasic rocks (Garde & Steenfelt 1989 and 1999). Large plagioclase crystal accumulations are found (“snowball” anorthosite, Figure 5). The structure is described as a series of thrust slices, with a large synform fold in the north-eastern part (Figure 6). No information about the composition of the Boye Sø anorthosite complex was available and no samples were available either.

Figure 5

“Snowball” anorthosite from Boye Sø. Photo A. Garde (from Garde & Steenfelt 1989).

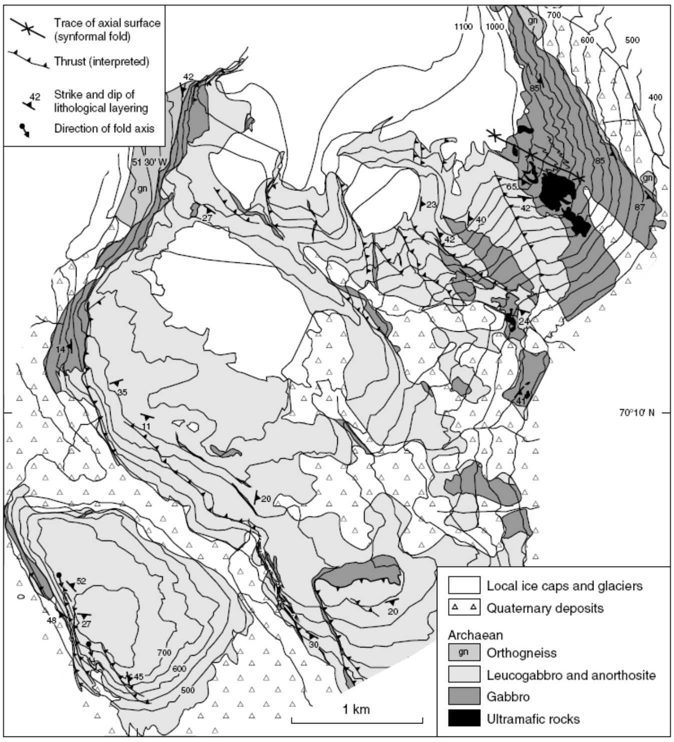


Figure 6

Map of the Boye Sø anorthosite complex (from Garde & Steenfelt 1989).

Qaqortorssuaq anorthosite

The anorthosite was found by Knud Ellitsgaard-Rasmussen in 1946 (Ellitsgaard-Rasmussen & Mouritsen, 1954) to form a very large body, which they estimated to contain a minimum of 3 to 4 km^3 of anorthosite. The anorthosite contains Kangamiut dyke fragments and is affected by the Nagssugtoqidian orogeny and is metamorphosed under amphibolite facies conditions.

Figure 7

The 1300 m high Qaqortorssuaq mountain. The outcrop on the mountain has the light color characteristic of anorthosite.

Photo Karsten Secher.

The anorthosite is a fine- to medium-grained rock sometimes with large ideoblastic grains. The colour is white to greyish in the purest varieties. Plagioclase and clinozoisite constitute the main minerals of the rock with minor amounts of hornblende, muscovite, biotite, chlorite, calcite, scapolite and quartz. The plagioclase has a slightly variable mineral composition (Table 4) and the grains are often zoned with lower An content towards the rim.

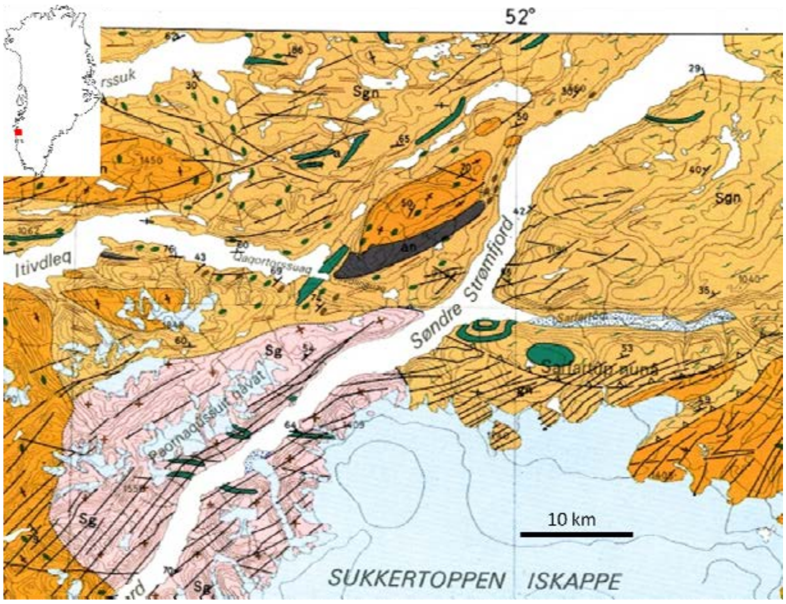


Figure 8

The location of the Qaqortorssuaq anorthosite just north of Søndre Strømfjord (grey). Allart (1982).

Exploration was carried out by Kryolitselskabet Øresund A/S (Gothenborg & Keto, 1977), who based on 52 samples taken in profiles estimated that ca. 100 mill tonnes of anorthosite could be mined per vertical meter of the deposit with an average Al_2O_3 content of 33,7 wt%. The chemical results found by both Ellitsgaard-Rasmussen & Mouritsen (1954) and Gothenborg & Keto (1977) could be reproduced in the present study (sample 472511, Table 3). The An content in the plagioclase varies from ca. 70 to 84 with a mean of ca. 79 % in the present study (Table 4), which is fairly close to what can be estimated from CIPW norm calculation based on the whole-rock analysis (Table 3).

Table 3 Whole rock analysis

	17476	17477	17478	2228	472511	Mean
SiO2	46,1	46,5	47,1	48,4	46,8	47,0
TiO2				0,0	0,0	0,0
Al2O3	33,8	34,1	33,1	33,2	32,4	33,3
Fe2O3	1,1	0,7	1,1	0,4	1,2	0,9
MgO	0,6	0,4	0,5	0,1	0,3	0,4
CaO	16,3	15,9	15,5	15,6	15,8	15,8
Na2O	2,0	2,3	2,3	2,1	2,2	2,2
K2O	0,1	0,1	0,4	0,0	0,2	0,2
	100	100	100	99,9	98,9	99,8
CIPW						
% An in plagioclase	85,1	82,8	82,2	80,3	81,7	82,4
Plagioclase	94,3	94,4	92,7	95,1	95,8	94,5

Table 4 Microprobe results from sample 472511

	SiO2	FeO	K2O	TiO2	Na2O	Al2O3	MnO	CaO	MgO	Total	% An
	49,4	0,06	0,03	0,00	2,3	33,4	0,03	16,4	0,00	101,7	79,7
	47,2	0,06	0,02	0,00	2,4	31,9	0,04	16,3	0,02	97,9	79,3
	48,0	0,00	0,00	0,01	2,3	32,6	0,05	16,5	0,00	99,4	79,7
	48,5	0,00	0,01	0,01	2,7	32,3	0,00	16,4	0,00	99,8	77,4
	48,3	0,01	0,02	0,00	2,2	32,7	0,02	16,8	0,00	100,0	80,5
	47,5	0,06	0,01	0,00	2,4	32,0	0,00	16,4	0,02	98,4	79,5
	48,4	0,04	0,01	0,00	2,6	31,8	0,00	16,0	0,00	98,8	77,2
	46,5	0,02	0,05	0,02	1,9	32,8	0,00	17,3	0,02	98,6	83,6
	48,2	0,09	0,01	0,00	2,5	32,5	0,00	16,5	0,01	99,8	78,9
	48,9	0,00	0,02	0,02	2,6	32,6	0,01	16,3	0,00	100,3	77,6
	48,2	0,00	0,02	0,01	2,6	32,7	0,00	16,5	0,00	100,0	77,8
	47,9	0,00	0,00	0,02	2,6	32,7	0,03	16,4	0,00	99,7	77,9
	47,2	0,00	0,02	0,02	2,3	32,5	0,00	16,7	0,01	98,7	80,1
	48,4	0,02	0,00	0,03	2,4	32,9	0,06	16,9	0,00	100,7	79,8
	48,9	0,03	0,03	0,00	2,5	32,5	0,02	16,5	0,00	100,4	78,3
	48,5	0,00	0,03	0,01	2,4	32,7	0,04	17,0	0,00	100,7	79,4
	48,3	0,01	0,02	0,02	2,5	32,2	0,01	16,5	0,00	99,5	78,5
	48,1	0,09	0,00	0,01	2,4	32,5	0,05	16,6	0,01	99,7	79,1
Mean	**48,1**	**0,03**	**0,02**	**0,01**	**2,5**	**32,5**	**0,02**	**16,6**	**0,00**	**99,8**	**79,1**

Akia anorthosite

A large occurrence of anorthosite belonging to the Akia terrain was found on the west coast of Akia/Nordlandet by Vic McGregor, who state that the anorthosite underwent granulite facies metamorphism at ca. 3.0 Ga (McGregor, 1993). The anorthosite has further been studied by Owens & Dymek (1997) and Dymek & Owens (2001). Berthelsen (1960) describes anorthosite and leucogabbro as continuous horizons and trains of inclusions that were very useful in mapping the structure of the Tovqussaq Nunâ to the north of Nordlandet and of Fiskefjord.

The anorthosite (Figure 9) forms a ca. 40 km^2 intrusion associated with amphibolite and metasediments (McGregor 1993). The body is highly fragmented and dissected by hypersthene-bearing gneisses.

Plagioclase typically occurs in a granular texture and is commonly ``dusted'', due to the presence of abundant sub-micron-sized opaque inclusions (Owens & Dymek, 1997). The plagioclase has a very large compositional range (An_{30-97}). Plagioclase compositional variation correlates with the nature of associated minerals. The most calcic plagioclase is related to spinel and corundum (Figure 10). Plagioclase in the vicinity of clinopyroxene are often reversely zoned with cores mostly An_{50-60} and rims up to An_{75}. Plagioclase in regions that contain amphibole is mostly in the An_{94-74} range.

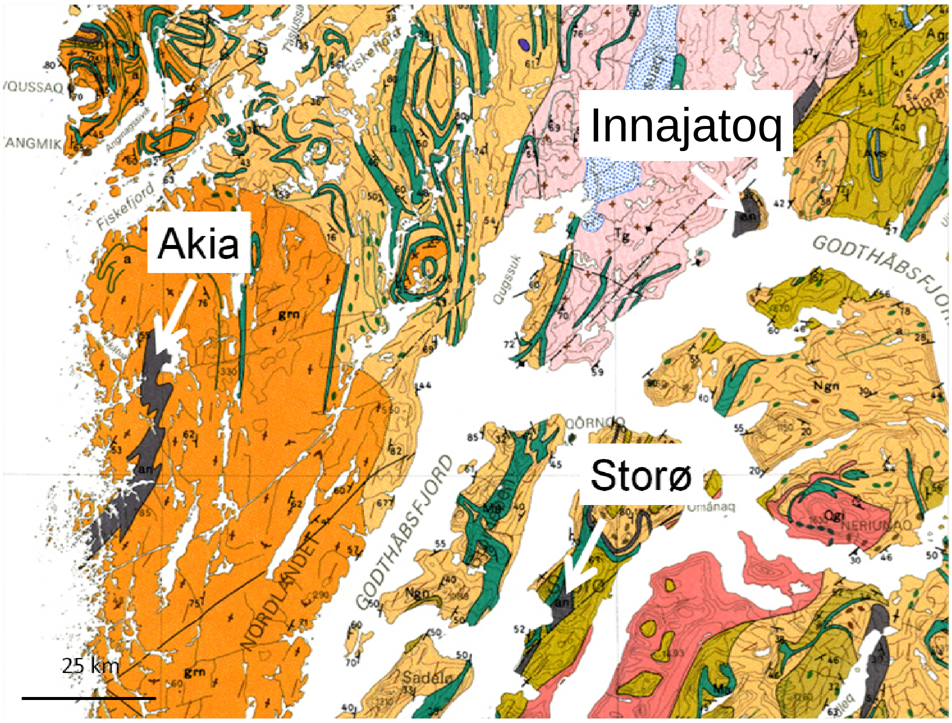


Figure 9 Geological map of the northern part of Godthåbsfjorden. Anorthosite is grey. Allart (1982)

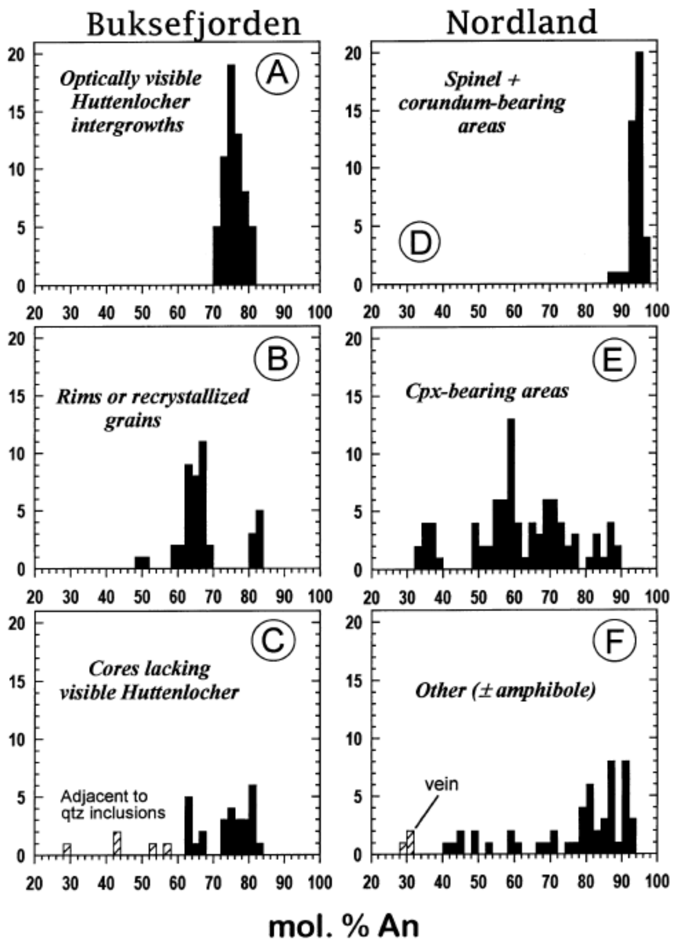


Figure 10

Plagioclase compositions from Nordlandet and Buksefjorden (Owens & Dymek, 1997).

The composition of the plagioclase varies with the texture and associated minerals.

Table 5 Whole rock analysis of anorthosites from Nordlandet Sample 339501 is from this work the rest is from Dymek & Owens (2001).

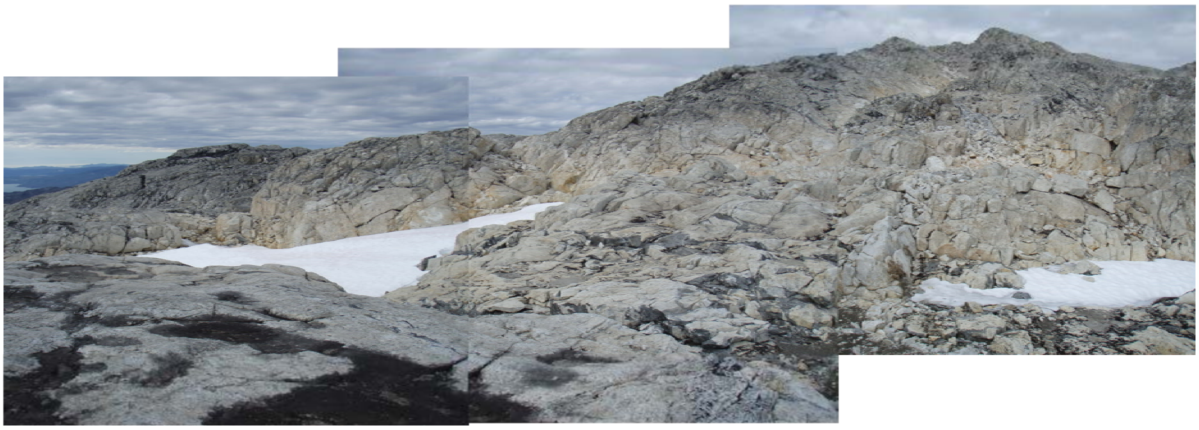
	OGD-71504	OGD-71505	OGA-14a	OGA-14b	OGA-41	OGG-66	OGG-69	OGG-70	339501	Mean
SiO2	47,31	48,14	49,18	50,65	46,05	51,09	44,12	44,72	47,13	47,7
TiO2	0,04	0,04	0,06	0,07	0,07	0,06	0,09	0,06	0,21	0,1
Al2O3	32,6	29,23	30,35	29,14	30,08	27,9	33,12	33,23	29,74	30,7
Fe2O3	0,93	2,04	1,56	1,76	2,39	1,75	1,82	1,56		1,7
FeO									2,73	
MnO	0,02	0,03	0,02	0,03	0,03	0,03	0,02	0,02	0,06	0,03
MgO	0,21	2,98	0,5	0,7	2,53	1,32	1,35	1,21	2,21	1,4
CaO	16,06	14,65	14,35	13,64	15,73	12,9	17,49	16,99	15,31	15,2
Na2O	2,05	2,14	2,77	3,33	1,72	3,55	0,92	1,19	1,88	2,2
K2O	0,17	0,24	0,21	0,27	0,31	0,31	0,29	0,23	0,29	0,3
P2O5	0,01	0,01	0,05	0,03	0,02	0,03	0,03	0,01	0,05	0
LOI	0,2	0,34	0,32	0,19	0,43	0,51	0,32	0,24	0,58	0,3
Sum	99,6	99,84	99,37	99,8	99,36	99,45	99,58	99,46	100,19	99,6
CIPW										
Calculated An	81,2	78,4	73,7	68,1	84,7	65,1	93,9	90,6	81	79,5
% Plagioclase	97,2	88,1	94,2	92,5	87,1	90,4	91,5	93,3	88,1	91,8

Innajatoq anorthosite

In the inner part of the Nuuk Fjord there is a conspicuous ca. 1000 m high white ca. 3 km * 3 km island entirely consisting of anorthosite (Figure 11).

Figure 11

Innajatoq anorthosite seen from the north-west (top), south-west (left) and in outcrop on top of the mountain (below).



The anorthosite is very homogeneous on outcrop scale.

However, the composition of the plagioclase varies (Figure 12) and the grains are zoned with rims with lower An content relative to the cores (Figure 13).

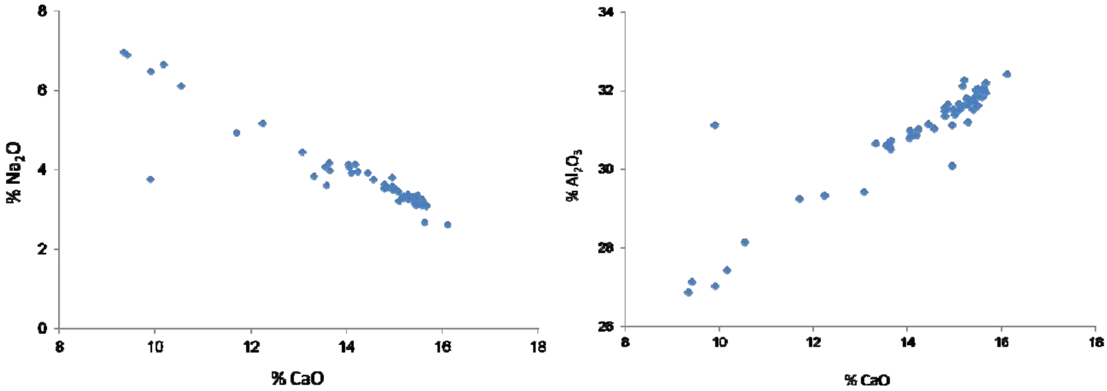


Figure 12 Plot of Na_2O and Al_2O_3 versus CaO in plagioclase from microprobe analysis of sample 473788 from Innajatoq anorthosite.

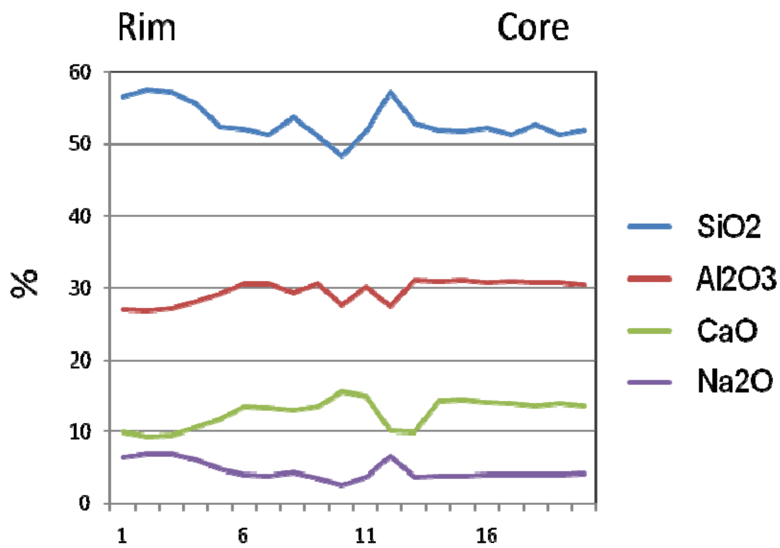


Figure 13

Microprobe profile 2 (30 mm long) in a plagioclase grain. Sample 473788.

	Profile 1	Profile 2	Profile 3	Whole rock
No	18	20	20	
SiO2	50,4	53,1	50,6	46,2
Al2O3	31,2	29,6	31,7	31,8
TiO2				0,05
FeO	0,1	0,1	0,0	1,5
MgO	0,1	0,2	0,0	0,7
MnO				0,02
CaO	15,4	12,7	15,2	16,0
Na2O	3,4	4,6	3,4	2,0
K2O	0,0	0,2	0,0	0,3
BaO	0,02	0,02	0,01	0,01
LOI				1,5
Total	100,5	100,4	101,0	100,0
% An	71,7	60,2	71,5	

Table 6

Microprobe analysis and whole rock

Storø anorthosite

The anorthosite grades from anorthosite to leucogabbro. There are large differences in strain partitioning and areas of low strain are represented by near igneous texture with amphiboles and large plagioclase crystals that only display minor recrystallisation at the rims (core-and-mantle structures). Higher strained areas are completely or near completely recrystallised with a grain size reduction. Minerals are commonly segregated into alternating bands of dominantly plagioclase and amphiboles.

The general mineralogy is plagioclase + hornblende +/- quartz +/- biotite +/- clinozoisite. Accessory phases are ilmenite, titanite, pyrite and muscovite. Titanite occurs as coronas/rims around ilmenite that also contain exsolution lamellae's of Fe-oxide. Pyrite is associated with ilmenite and contains exsolution of chalcopyrite. The hydrated minerals are mostly associated with amphibole-rich bands.

Figure 14 The Storø anorthosite. The thickness of the anorthosite is ca 500 m here.

Three generations of plagioclase grains are separable:

- Magmatic cm sized grains,
- 1st generation of recrystallised grains (average grain size 400µm and having the same composition as the magmatic host grains, An_{80}). Some of these grains have a rim (asymmetric zoning) with a lower An content (An_{65}).
- 2nd generation of recrystallised grains. These grains emanate from the rims of the 1st generation and have the same composition as the rims, An_{65}.

Microstructures show that two ductile deformation events are preserved. The first event show dynamic recrystallisation, i.e. same composition in recrystallised grains as in the hosts (Magmatic grains → 1st generation of recrystallised grains). The second event was aided by fluids and caused recrystallisation with a chemical change (1st → 2nd generation of recrystallised grains). Later lower temperature events are seen by fractures (filled with hydrated minerals) that cross-cuts both magmatic grains and the 1st and 2nd generation of recrystallised grains.

Table 7 Plagioclase and whole rock compositions at Storøen

	Microprobe	Microprobe	Microprobe	Whole rock
	Igneous	Metam. core	Metam. rim	468049
No of anal.	11	61	30	
SiO2	47,86	47,96	52,02	47,06
TiO2				0,04
Al2O3	33,58	33,37	30,72	32,34
FeO	0,04	0,14	0,04	0,83
MnO				0,01
MgO				0,41
CaO	16,57	16,55	13,38	16,03
Na2O	2,24	2,26	4,1	2,08
K2O	0,01	0,01	0,02	0,13
P2O5				0,03
LOI				0,64
Total	100,3	100,3	100,28	99,6
				Calculated
An in plag.	80,27	80,2	64,28	81,3
				CIPW
			Plagioclase	96,6
			Orthoclase	0,8
			Diopside	0,7
			Hypersthene	0
			Olivine	1,4
			Ilmenite	0,1
			Magnetite	0,1
			Apatite	0,1

Naajat Kuuat anortohosite

The Naajat Kuuat anorthosite (Figure 15) complex occurs as kilometre scale folded bodies with variable content of hornblende (Figure 16). The anorthosite occurs together with amphibolite and ultramafic rocks (Figure 17) some of which form lensoid bodies up to > 500 m long and 200 m wide. The composition of these ultramafic rocks varies from dunites over hartzburgites, spinel-lherzolites, garnet-lherzolites to olivine websterite (Solgevik, 2009).

Figure 15
Anorthosite from Naajat Kuuat.

The general mineralogy is plagioclase + hornblende +/- quartz +/- biotite +/- clinozoisite, and the content of amphibole varies.

Figure 16
Anorthosite to leucogabbro from Naajat Kuuat.

Accessory phases are ilmenite, titanite and zircon. The anorthosite grades between leucogabbro and anorthosite. It dominantly contains magmatic plagioclase grains with core-and-mantle structure (rim of recrystallised grains has lower An content) and intercumulus (interpretation) amphiboles.

The anorthosite is cut by tonalitic gneiss. Thin sections from Naajat Kuuat display cleaner plagioclase as compared to anorthosite from Storø and Quarliit-Nunaat.

Table 8 Whole rock analysis of anorthosite from Naajat Kuuat

	496647	477950	477951	486050	486031	486020	Mean
SiO2	51,851	48,901	47,819	49,13	49,87	48,03	49,3
TiO2	0,052	0,082	0,091	0,08	0,09	0,1	0,1
Al2O3	29,717	31,872	31,369	30,01	28,75	29,79	30,3
Fe2O3	0,794	0,53	0,291	2,12	2,47	2,58	1,5
FeO		0,59	1,2				0,9
MnO	0,011	0,019	0,031	0,03	0,04	0,05	0,0
MgO	0,344	0,327	0,897	1,21	1,63	1,54	1,0
CaO	13,468	15,343	15,254	14,79	13,9	15,4	14,7
Na2O	3,08	2,27	2,15	2,27	2,77	2,25	2,5
K2O	0,213	0,187	0,317	0,35	0,49	0,27	0,3
P2O5	0,014	0,01	0,013	na	na	na	0,0
LOI	0,73	0,446	0,634	na	na	na	0,6
Total	100,27	100,58	100,07	100	100	100	100,2
Calculated							
An in plag	70,6	78,9	79,6	77,6	72,2	78,5	76,2
CIPW							
Quartz	3,33	0,9	0	0,3	0	0	0,8
Plagioclase	93,2	95,2	93,7	90,1	88,2	88,7	91,5
Orthoclase	1,2	1,1	1,9	2,1	2,9	1,6	1,8
Diopside	0,1	0	0,5	2,3	3,6	5	1,9
Hypersthene	1,9	2,4	1,4	4,8	2,1	0	2,1
Olivine	0	0	2,1	0	2,6	3,6	1,4
Ilmenite	0,1	0,2	0,2	0,2	0,2	0,2	0,2
Magnetite	0,1	0,2	0,2	0,3	0,4	0,4	0,3

Table 9 Microprobe analysis of plagioclase from Naajat Kuuat anorthosite

	Rim	Rim	Rim	Rim	Rim	Core	Core	Core	Core	Core	Mean
SiO2	48,00	47,88	47,52	47,65	47,53	47,81	47,50	47,50	47,28	48,01	47,70
TiO2	0,00	0,00	0,02	0,00	0,00	0,00	0,00	0,00	0,01	0,00	0,00
Al2O3	33,14	32,91	33,28	33,20	33,01	33,17	32,98	33,84	33,99	33,17	33,10
Cr2O3	0,11	0,00	0,00	0,00	0,03	0,00	0,00	0,01	0,02	0,02	0,02
FeO	0,12	0,12	0,06	0,18	0,13	0,22	0,10	0,12	0,05	0,10	0,13
MnO	0,00	0,00	0,03	0,06	0,04	0,05	0,00	0,03	0,06	0,04	0,03
MgO	0,01	0,01	0,00	0,03	0,02	0,01	0,00	0,00	0,00	0,02	0,01
CaO	16,93	16,66	16,86	16,78	16,84	16,87	16,98	17,30	17,28	16,96	16,85
Na2O	2,21	2,25	2,21	2,23	2,16	2,13	2,11	2,02	1,84	2,18	2,19
K2O	0,05	0,03	0,03	0,05	0,03	0,04	0,02	0,03	0,01	0,02	0,03
Cl	0,00	0,00	0,01	0,00	0,00	0,00	0,00	0,00	0,01	0,00	0,00
F	0,02	0,00	0,00	0,00	0,01	0,00	0,01	0,00	0,00	0,00	0,01
Total	100,59	99,87	100,01	100,18	99,80	100,30	99,72	100,84	100,55	100,52	100,07
An	0,81	0,80	0,81	0,80	0,81	0,81	0,82	0,82	0,84	0,81	0,81

The plagioclase is calcic with an around An_{80} (Table 9). The calculated An based on bulk rock composition is slightly lower but close to what is measured with the microprobe. There is little zoning of the plagioclase at Naajat Kuuat (Table 9).

Qarliit Nunaat anorthosite

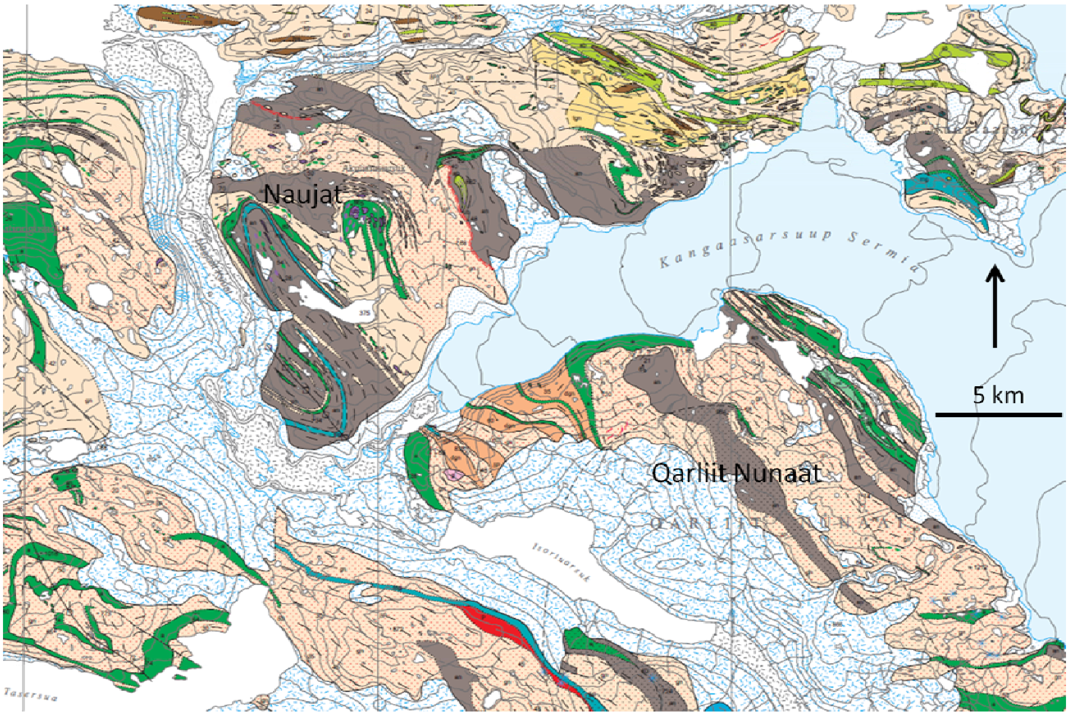


Figure 17 Location of the Naajat Kuuat and Qarliit-Nunaat anorthosites (grey). From the Kapisiliit 1:100.000 geological map (Rehnström 2012).

The Qarliit Nunaat anorthosite complex probably links up with Naajat Kuuat anorthosite complex to the north (Figure 17). The anorthosite occur as less deformed lenses surrounded by a continuous network of anatomizing higher strained zones. Display magmatic plagioclase grains (~An_{80}) that are recrystallised (core-and-mantle structure) where the new grains have a lower An content. They have in turn been recrystallised in the above mentioned shear zones but with a little increase in An. Thus, two ductile deformation events are recorded by these observations. Locally intense later epidotisation (related to more or less brittle fractures).

Magmatic grains from the less deformed part of the anorthosite-leucogabbro have an average anorthite content of An_{79} decreasing to An_{62} at the rim (Solgevik & Piazolo, in press). The first generation of recrystallised grains (>500 μm) exhibits An_{42} to An_{74}. Those that act as porphyroclasts, have an average of An_{44} whereas the second generations of recrystallised grains show an average of An_{46} (Figure 18 and Table 9). The only available whole rock chemical analysis from Qarliit Nunaat anorthosite show a Na rich composition.

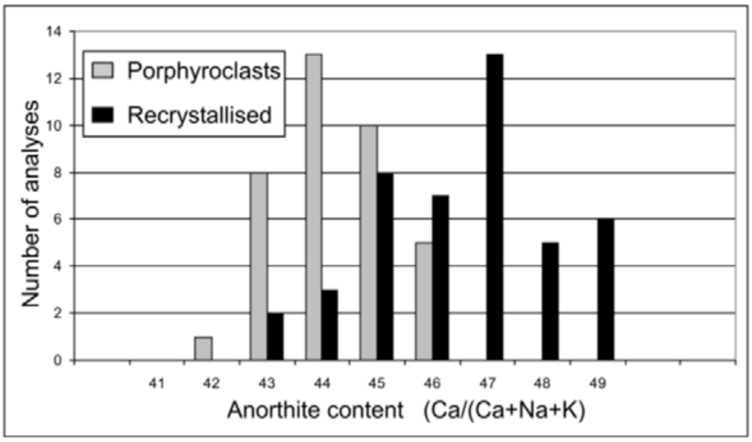


Figure 18

Difference between 1.st generation recrystalligrains (porphyroclasts) and 2.nd generation recrystallised plagioclase from the Qarlit-Nunaat anorthosite. Svahnberg & Piazolo (2010).

Table 10 Microprobe and whole rock data from the Qarlit-Nunaat anorthosite

	Microprobe	Microprobe	Whole rock
	Igneous	Metamorphic	
GEUS no	468022	468022	468030
No of anal.	22	28	
SiO2	56,3	56	53,73
TiO2			0,10
Al2O3	26,5	27,1	28,49
Fe2O3	0	0	0,01
FeO	0,1	0,1	0,87
MnO			0,01
MgO			0,31
CaO	9,5	9,8	11,88
Na2O	6,5	6,3	4,13
K2O	0,1	0,1	0,41
P2O5			0,02
LOI			0,47
Total	99,1	99,5	100,43
% An in plagioclase	44,2	46,1	61,0

Quartz	1,9
Plagioclase	93,0
Orthoclase	2,4
Diopside	0,7
Hypersthene	1,7

Buksefjorden anorthosite

The Buksefjorden anorthosite (Figure 19) was first described by Sørensen (1955) and forms an elongate ca. 25 km long and ca. 0.5 km thick, folded, stratiform body that is largely intact, but invaded along its margins by ca. 2.8 Ga gneisses. The anorthosite consists almost entirely of white to pale gray plagioclase and dark green Ca-amphibole, with minor amounts of pale-green epidote (Owens & Dymek, 1997). It occur together with aluminous gneisses (para-gneisses) which led Sørensen (1955) to suggest that the anorthosite "may be of sedimentary origin".

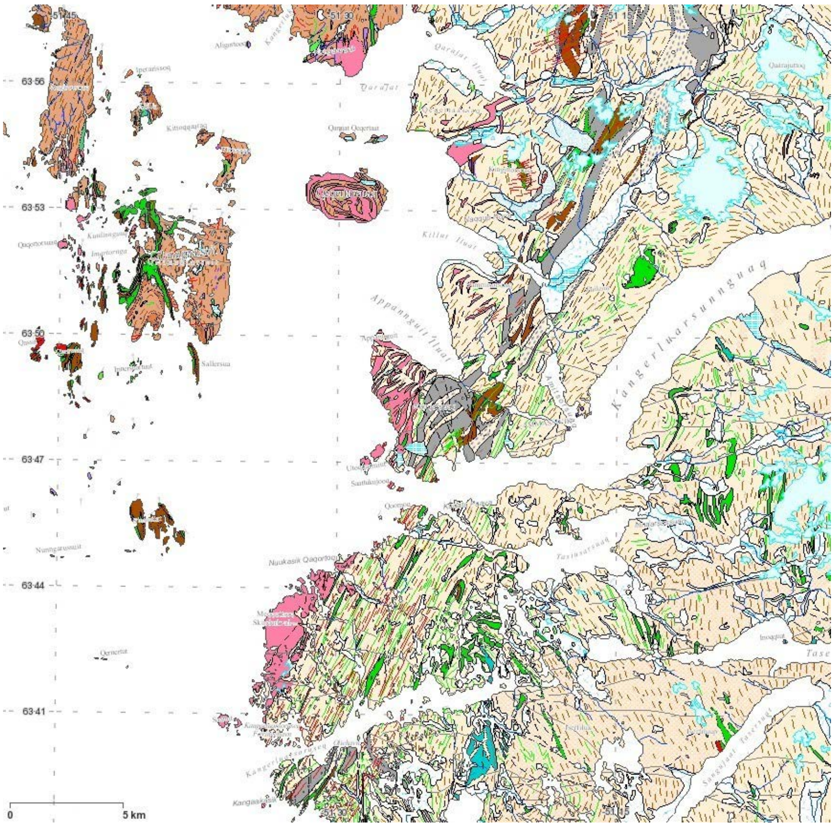


Figure 19

Geological map of the Buksefjorden area. The anorthosite is grey on the map. Allart (1982)

Modal plagioclase ranges from >95 to ca. 50%, such that the samples include anorthosite, leucogabbro and metagabbro.

The body is texturally heterogeneous, ranging from white to pale gray anorthosite with elongate (ca. 2±4 cm long), irregularly-shaped clots and streaks of amphibole. Plagioclase typically occurs as anhedral, subequant to slightly elongate grains generally ½ to 2 mm in size (Owens & Dymek, 1997). Deformation is evident in the form of bent twin lamellae and the development of sub-grain boundaries. In some cases, larger crystals are surrounded by zones of smaller (ca. 0.25 mm) polygonal grains (Figure 20a), indicating some degree of recrystallisation. Many of the larger grains contain numerous tiny (<0.05 mm long), euhedral, randomly oriented inclusions of Ca-amphibole (Figure 20b). Huttenlocher intergrowths are common in plagioclase cores, but are typically absent from rims (Figure 20c).

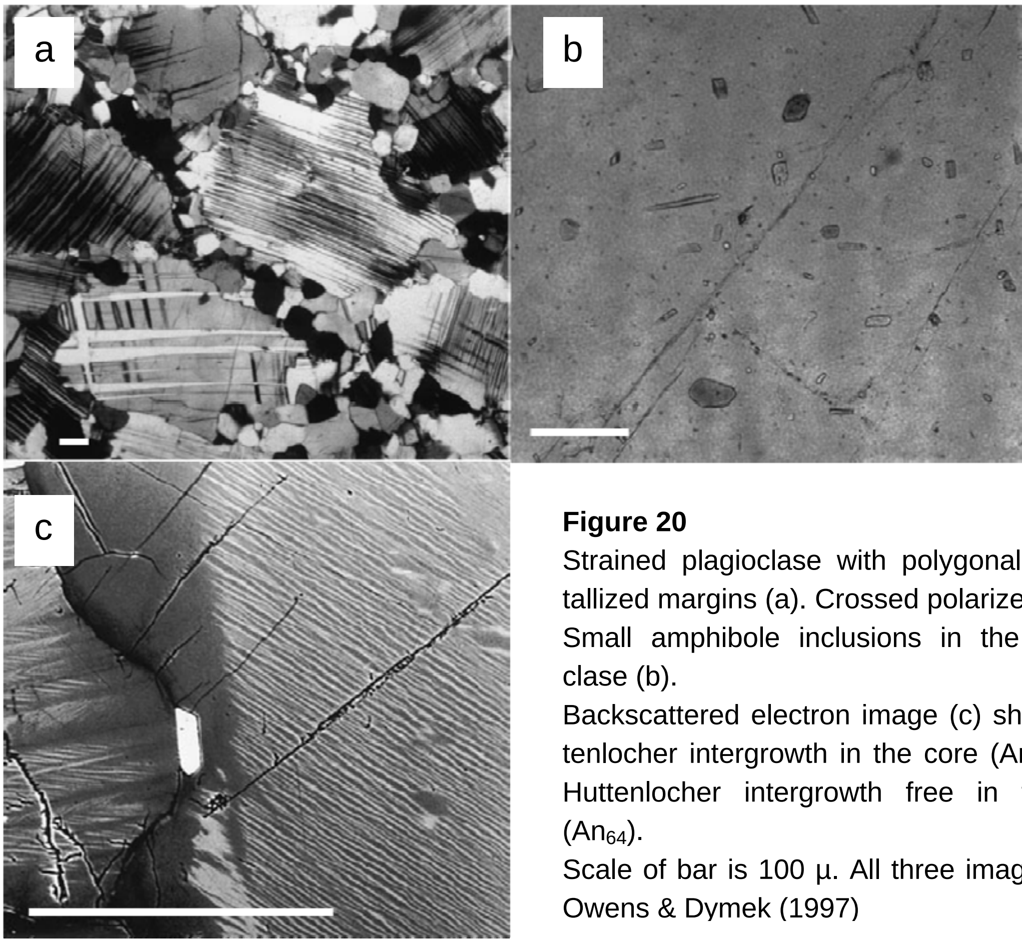


Figure 20
Strained plagioclase with polygonal recrystallized margins (a). Crossed polarized light.
Small amphibole inclusions in the plagioclase (b).
Backscattered electron image (c) show Huttenlocher intergrowth in the core (An_{75}) and Huttenlocher intergrowth free in the rim (An_{64}).
Scale of bar is 100 µ. All three images from Owens & Dymek (1997)

Table 11 Buksefjorden anorthosite whole rock compositions (from Dymek & Owens, 2001)

	OGD-72603	OGD-72605	OGD-72606	OGD-72608	OGG-138	OGG-142
SiO2	55,55	48,99	49,49	52,94	48,78	47,68
TiO2	0,07	0,06	0,04	0,04	0,04	0,05
Al2O3	26,02	29,24	29,8	28,79	30,65	31,02
Fe2O3	1,3	2,05	1,67	0,77	1,13	1,47
MnO	0,02	0,04	0,02	0,01	0,02	0,02
MgO	1,14	1,4	0,9	0,23	0,89	1
CaO	11,56	14,63	14,5	12,72	15,05	16,07
Na2O	3,28	2,47	2,54	3,35	2,44	1,86
K2O	0,22	0,2	0,18	0,16	0,2	0,11
P2O5	0,03	0,01	0,01	0,01	0,05	0,01
LOI	0,35	0,33	0,31	0,23	0,45	0,35
	99,53	99,42	99,47	99,24	99,7	99,64
Calc. An in plag.	65,4	75,4	75,2	67,7	76,7	81,9
Quartz	8,87	0,09	1,11	4,84	0,17	0,4
Plagioclase	84,2	90	91,8	92,4	93,5	92,5
Orthoclase	1,3	1,2	1,1	1	1,2	0,7
Diopside	1,2	3,7	2,1	0	1,9	3,1
Hypersthene	4	4,6	3,6	1,6	2,9	3
Ilmenite	0,1	0,1	0,1	0,1	0,1	0,1
Magnetite	0,2	0,3	0,3	0,1	0,2	0,2

Fiskenæsset anorthosite

Fiskenæsset anorthosite is one of the largest and best known Archaean anorthosite complexes. Parts of the Fiskenæsset Complex retains its igneous stratigraphy, cumulate textures, layering, grading and channel deposits (Windley et al., 1973, Windley & Smith. 1974; Myers, 1975, 1976, 1985), and it is concluded that the Fiskenæsset Complex is a sheet-like, layered basic intrusion. Based on insitu $^{207}Pb/^{206}Pb$ zircon ages of up to 2.95 ± 0.03 Ga Keulen et al (2010) interpret the intrusion age to be ca. 2.97-2.95 Ga.

The igneous stratigraphy of the Fiskenæsset Complex was identified by Windley (1973) and Myers (1985) worked out a stratigraphy for the whole complex. The main stratigraphic units are from bottom to top: Lower Gabbro, Ultramafic Unit, Lower Leucogabbro, Middle Gabbro, Upper Leucogabbro, Anorthosite and Upper Gabbro (Figure 23 & 24). The anorthosite unit is ca. 250 m thick (Myers, 1985). Where the anorthosite is least deformed, it typically appears as megacrystic with 1 – 10 cm relict igneous equant plagioclase grains dispersed in 1 – 5 mm large metamorphic plagioclase. The main part of the anorthosite is deformed and the plagioclase is metamorphic in a granular texture.

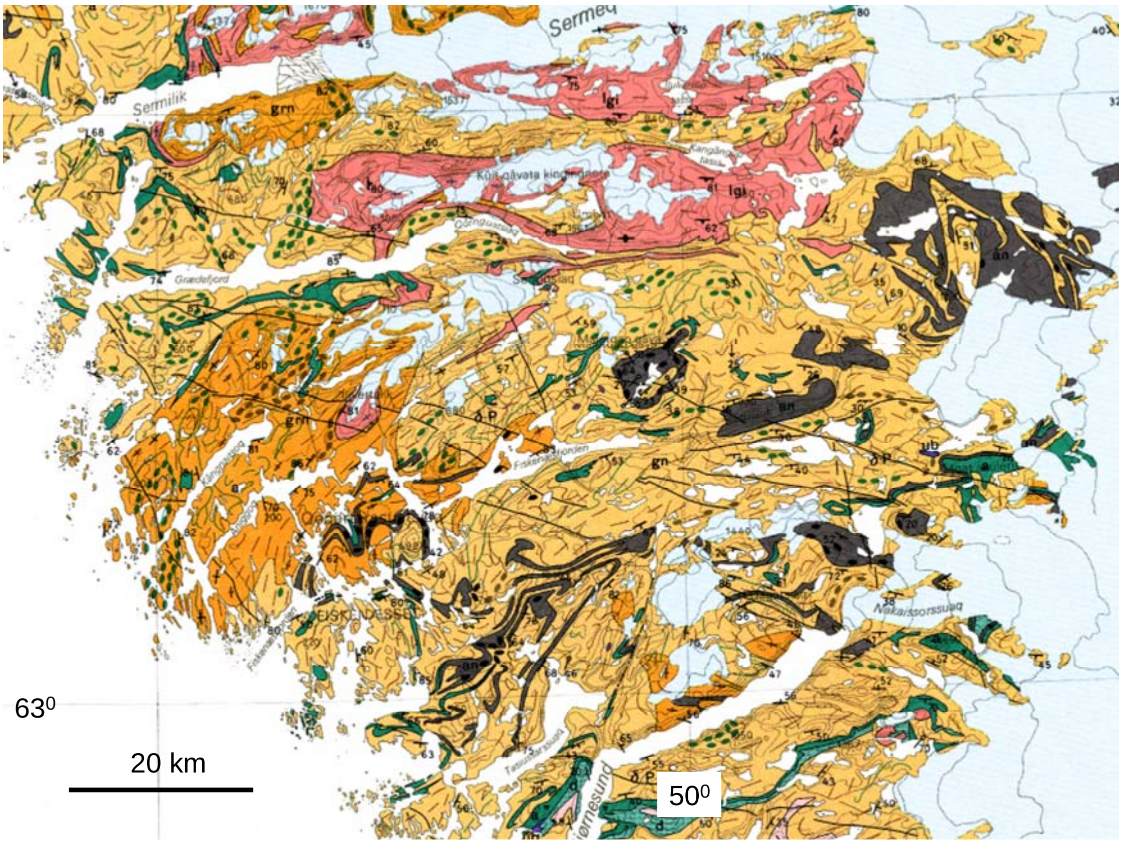


Figure 21 Geological map of the Fiskenæsset anorthosite complex (grey). (Allart, 1982)

Figure 22

Fiskenæsset anorthosite with the typical light weathering colour. Photo A. Scherstén.

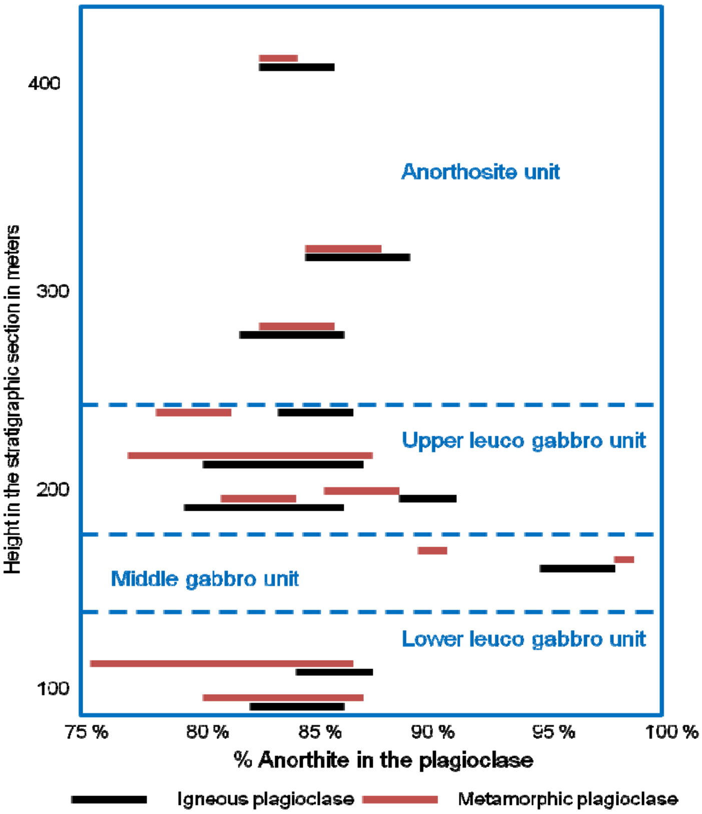


Figure 23

Compositional variation in the plagioclase composition with stratigraphic position in the Fiskenæsset anorthosite. After Myers & Platt (1977).

Myers & Platt find a variation with stratigraphic height, but not very systematic. The only very clear signal is that the plagioclases in the middle gabbro unit is consistently richer in anorthite (An_{98}-$_{94}$).

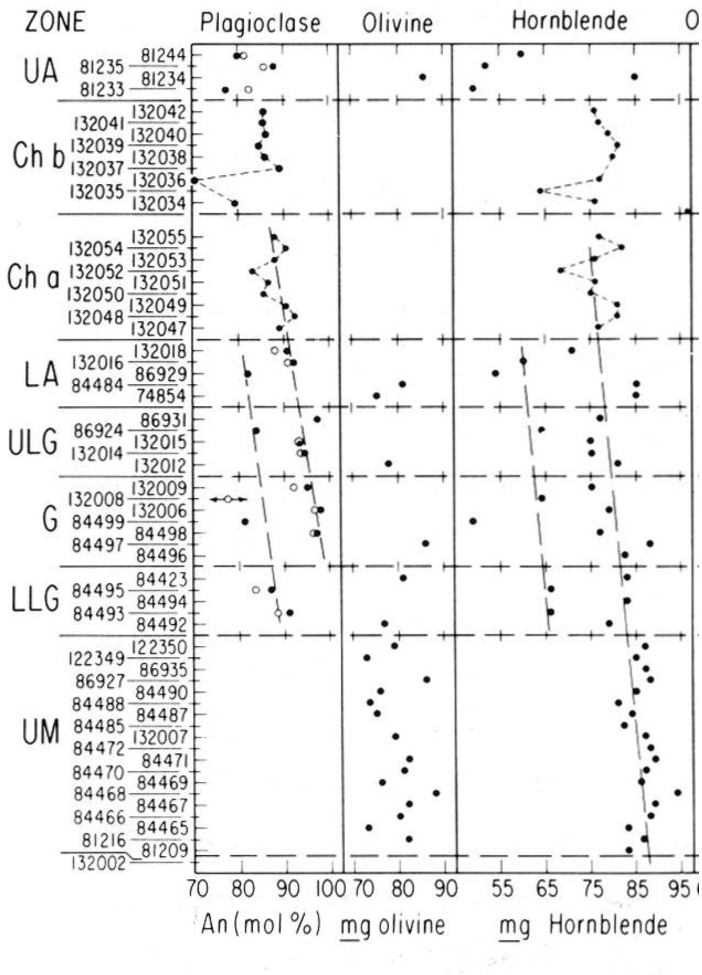


Figure 24

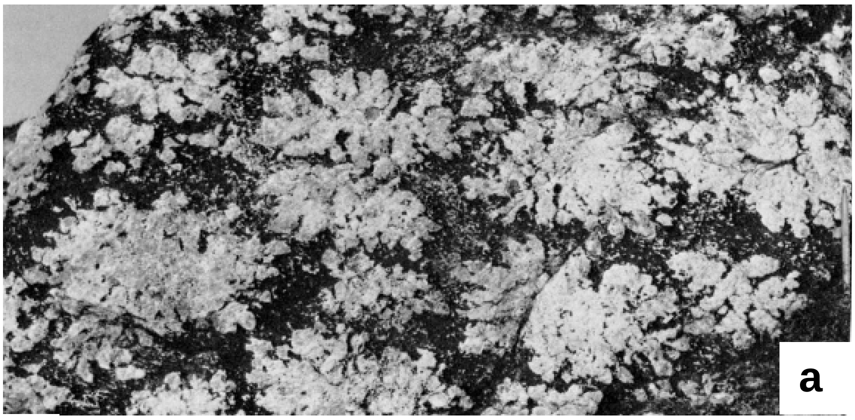
Compositional variation in the plagioclase, olivine and hornblende with stratigraphic position.

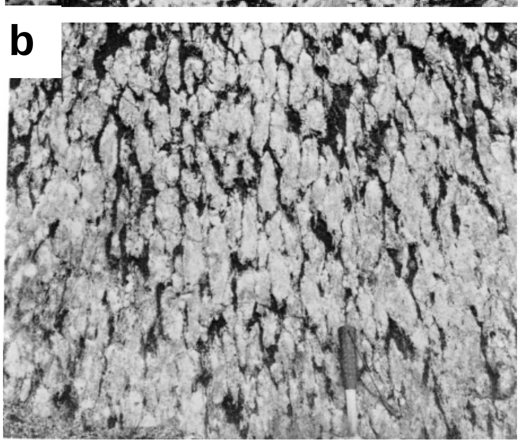
LLG correspond to Lower leuco gabbro unit on Figure 23 and the top of the figure correspond to the top of Figure 23. From Steele et al (1977).

.

Steele et al. (1977) find a rather systematic decrease in anorthite content with stratigraphic height (Figure 24).

Myers & Platt (1977) notice that there is an outwards decrease in the anorthite content in zoned igneous plagioclase with cores generally in the range An_{89-85} and margins in the range An_{84-79}. Recrystallisation during metamorphism along margins of the original grains is common as well as it occur along cross-cutting fractures of the primary grains. The composition of the secondary grains mimics the composition of the primary igneous crystal in the immediate proximity indicating that no significant change in plagioclase compositions occurred during metamorphism. True margins of the primary plagioclases may then be equivalent in composition to the most sodic secondary plagioclases. Myers & Platt (1977) also state that most plagioclases in the leucogabbro and anorthosite units are broadly similar in composition and range from An_{90} to An_{75}.





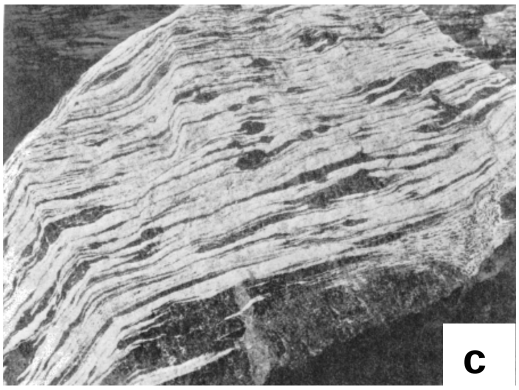


Figure 25

a) “Snow-flake” plagioclase aggregates in gabbro. Pencil for scale to the right in the picture. (From Myers, 1985)
b) Metamorphic aggregates after large equant igneous plagioclase deformed and recrystallised into prolate elipsoids in leucogabbro. (From Myers, 1985)
c) Aggregates after large equant igneous plagioclase deformed and recrystallised into oblate ellipsoids - in leucogabbro. (From Myers,

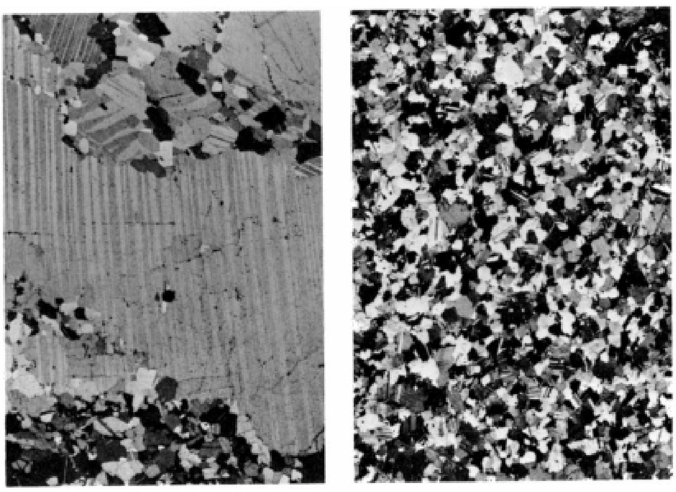


Figure 26

Photomicrographs of large, slightly deformed igneous plagioclase crystal (left) with finer grained metamorphic grains along the rim.
Granular metamorphic texture in anorthosite (right).
Crossed nicholls, 2 cm across (Myers, 1985).

Polat et al (2009) divided the anorthosites in to four major groups based on their REE patterns:

1. displays moderately depleted to slightly enriched LREE and HREE patterns;
2. possesses strongly enriched LREE and moderately depleted HREE patterns;
3. has strongly enriched LREE and depleted HREE patterns;
4. exhibits concave-upward REE patterns (garnet bearing)

Table 12 Mean anorthosite compositions based on Polat et al (2009)

	Mean Gr 1	Mean Gr 2	Mean Gr 3	Undifferent.	Mean All
N	9	3	3	2	
SiO2	46,2	46,5	50,7	47,2	47,2
TiO2	0,2	0,0	0,1	0,1	0,1
Al2O3	30,7	32,5	30,5	31,8	31,1
Fe2O3	2,8	1,9	1,5	1,8	2,2
MnO	0,0	0,1	0,0	0,0	0,0
MgO	1,6	0,7	0,4	0,8	1,2
CaO	16,7	16,3	12,5	15,9	15,7
Na2O	1,5	1,8	4,0	1,8	2,1
K2O	0,1	0,1	0,4	0,7	0,3
P2O5	0,02	0,01	0,01	0,01	0,02
LOI	0,6	0,5	0,5	1,8	0,7
Sum	100,6	100,4	100,6	101,8	100,6
CIPW					
% An in plag.	85,8	83,6	65,7	85,6	81,7
Quartz	0,0	0,0	0,0	0,5	0,1
Plagioclase	88,6	94,1	92,4	88,9	90,0
Orthoclase	0,7	0,8	2,4	3,9	1,7
Nepheline	0,7	0,2	1,6	1,7	1,0
Corundum	0,0	0,4	0,9	0,1	0,3
Diopside	5,3	1,1	0,0	1,7	3,0
Hypersthene	0,3	0,3	0,0	1,1	0,3
Wollastonite	0,0	0,0	0,0	0,0	0,0
Olivine	3,6	2,7	2,3	1,9	3,1
Ilmenite	0,4	0,1	0,1	0,2	0,3
Magnetite	0,4	0,3	0,2	0,3	0,3

Table 13 Fiskenæsset anorthosite whole rock compositions (from Polat et al, 2009).

	Group 1							Group 2		
	478805	478824	478826	478827	478853	478854	478855	478816	478825	478831
SiO2	46,3	46,4	46,2	46,2	45,8	45,6	46,3	46,8	46,7	46,1
TiO2	0,16	0,06	0,16	0,27	0,19	0,19	0,17	0,03	0,06	0,03
Al2O3	29,6	31,4	31	29,6	31,9	31,5	30,8	33,1	32,8	31,6
Fe2O3	3,3	1,8	2,6	3,7	2,2	2,7	2,6	0,7	1,2	3,9
MnO	0,05	0,03	0,03	0,06	0,03	0,04	0,04	0,01	0,02	0,14
MgO	1,8	1,5	1,5	2,3	1,1	1,4	1,5	0,3	0,6	1,2
CaO	17,2	17,5	16,7	16	17,2	16,9	17,1	17,1	16,8	14,9
Na2O	1,4	1,2	1,6	1,7	1,5	1,5	1,5	1,7	1,7	1,9
K2O	0,1	0,1	0,2	0,1	0,1	0,1	0,1	0,1	0,1	0,2
P2O5	0,02	0,01	0,01	0,01	0,03	0,02	0,02	0,01	0,01	0,02
LOI	0,56	0,52	0,61	0,56	0,54	0,63	0,75	0,35	0,65	0,45
	100,49	100,52	100,61	100,5	100,59	100,58	100,88	100,2	100,64	100,44
CIPW										
An in plagiocla-se	86	88,1	86,2	83,7	87,8	87,6	86,1	84,9	84,6	81,2
Quartz	0	0	0	0	0	0	0	0	0	0
Plagioclase	85,9	90,3	88,7	86,6	90,7	89,7	88,8	96,4	95,7	90,2
Orthoclase	0,6	0,6	1,2	0,6	0,6	0,6	0,6	0,6	0,6	1,2
Nepheline	0,3	0	1	0,6	1,2	1,2	0,5	0,3	0,2	0
Diopside	9,1	5,5	4,9	5,3	4,3	4	6,4	0	0	1,2
Hypersthene	0	2,3	0	0	0	0	0	2	1,4	0
Olivine	3,3	0,9	3,5	5,9	2,6	3,7	3	0	0	0,9
Ilmenite	0,3	0,1	0,3	0,5	0,4	0,4	0,3	0	0	0
Magnetite	0,5	0,3	0,4	0,5	0,3	0,4	0,4	0,5	1,8	5,9

	Group 3			Ungrouped	
	478839	478840	478842	478847a	478869a
SiO2	50,2	49,3	52,6	44,7	47,4
TiO2	0,07	0,05	0,03	0,11	0,04
Al2O3	30,6	31,5	29,5	25,3	31,8
Fe2O3	1,8	1,7	0,9	7,9	1,5
MnO	0,03	0,03	0,01	0,1	0,02
MgO	0,7	0,4	0,2	3,5	2,2
CaO	12,3	13,1	12	13	16,9
Na2O	3,9	3,5	4,5	0,8	1,5
K2O	0,4	0,5	0,3	0,3	0,1
P2O5	0,01	0,01	0,01	0,01	0,01
LOI	0,51	0,58	0,41	2,85	1,15
	100,52	100,67	100,46	102,77	101,12
CIPW					
% An in plag.	65,8	70,5	60,7	89,9	85,6
Quartz	0	0	0	0	1
Plagioclase	91	90,6	95,7	71,8	92,6
Orthoclase	2,4	3	1,8	1,8	0,6
Nepheline	1,7	2,2	1	0	0
Corundum	1,4	1,4	0	0	3,4
Diopside	0	0	0	10,4	2,2
Hypersthene	0	0	0	0	0
Wollastonite	0	0	0	14,7	0
Olivine	3,1	2,5	1,3	0,2	0,1
Ilmenite	0,1	0,1	0,1	1,2	0,2

Only anorthosite analyses from Polat et al (2009) with more than 85 % normative plagioclase has been included. Group 1 and 2 has according to CIPW calculations plagioclase compositions around $An_{86\text{-}83}$ in the same range as noted by Myers and Platt (1977) (Figure 23), whereas Group 3 has considerably lower Ca in the plagioclase. Group 4 does not seem to be anorthosite as the normative plagioclase content is below 80 %

Table 14 Microprobe analysis of plagioclase in anorthosite from Fiskenæsset (from Rollinson et al. 2010)

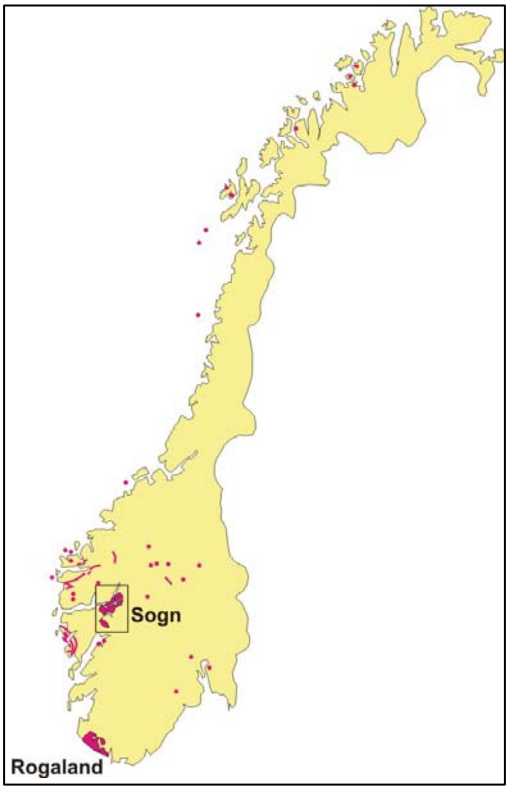
Sample:	47	47	49	49	50	50	52	52	54	54	55	55
SiO_2	46.45	46.19	45.19	45.53	46.09	46.18	56.20	55.28	45.61	45.46	45.00	46.51
TiO_2	0.00	0.00	0.00	0.01	0.00	0.01	nd	nd	0.01	0.00	0.00	0.01
Al_2O_3	33.81	33.61	34.41	34.64	33.67	33.68	27.24	27.59	34.88	34.70	34.54	34.31
Cr_2O_3	0.00	0.02	0.00	0.00	0.00	0.00	nd	nd	0.02	0.00	0.00	0.11
MgO	0.01	0.00	0.00	0.01	0.00	0.00	nd	nd	0.01	0.01	0.00	0.00
CaO	17.89	17.96	18.73	18.62	17.93	17.77	9.66	10.32	18.47	18.51	18.52	18.19
MnO	0.00	0.00	0.03	0.00	0.03	0.01	nd	nd	0.00	0.02	0.00	0.00
FeO	0.04	0.05	0.06	0.05	0.03	0.00	0.11	0.04	0.11	0.07	0.14	0.15
Na_2O	1.55	1.51	1.04	1.13	1.62	1.53	6.25	5.93	1.11	1.05	1.14	0.98
K_2O	0.00	0.00	0.01	0.00	0.01	0.02	nd	nd	0.02	0.00	0.00	0.00
Total	99.75	99.35	99.47	99.97	99.37	99.19	99.46	99.16	100.24	99.82	99.35	100.26
Cations to 32 oxygens												
Si	8.572	8.564	8.388	8.404	8.548	8.568	10.156	10.040	8.392	8.400	8.364	8.536
Ti	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Al	7.352	7.344	7.528	7.536	7.360	7.364	5.804	5.908	7.564	7.556	7.568	7.420
Cr	0.000	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.000	0.000	0.016
Mg	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.004	0.000	0.000
Ca	3.540	3.568	3.724	3.680	3.564	3.532	1.872	2.008	3.644	3.664	3.688	3.576
Mn	0.000	0.000	0.004	0.000	0.004	0.000	0.000	0.000	0.000	0.004	0.000	0.000
Fe	0.004	0.008	0.008	0.008	0.004	0.000	0.016	0.008	0.016	0.012	0.020	0.024
Na	0.552	0.544	0.376	0.404	0.580	0.548	2.188	2.088	0.396	0.376	0.412	0.348
K	0.000	0.000	0.000	0.000	0.004	0.004	0.000	0.000	0.004	0.000	0.000	0.000
An	0.865	0.868	0.908	0.901	0.859	0.865	0.461	0.490	0.902	0.907	0.900	0.911

The plagioclase is generally very calsic and the in the range An_{86} to An_{91} but Rollinson et al. (2010) locally find high Na in sample 52 (Table 14). This sample may represent Group 3 described by Polat et al (2009). Rollinson et al (2010) further find a small increase in the An content of the plagioclases with stratigraphic height from about An_{86} to An_{91}, although the trend within the intrusion as a whole is from higher to lower An content with increasing stratigraphic height (Steele et al.1977).

Neria anorthosite

The southernmost occurrence of Archaean anorthosite is described from Neria by Kalsbeek (1970). Here he found "leucocratic gneisses with anorthositic composition", which locally are nearly pure plagioclase rock. The anorthositic gneisses are clearly foliated locally with indistinctive banding.

The Norwegian experience



Anorthositic rocks are present in various parts of Norway (Figure 27) 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 elevated calcium-aluminium type (An_{50-78}).

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 aggregates and filler purposes.

Figure 27 Distribution of anorthosites in Norway (Wanvik, 2000).

Table 15 Chemistry of unaltered anorthosite in the two main 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

Norwegian prospecting for anorthosites

The first investigations of the anorthosites in Sogn for industrial use were made in 1917 by the renowned geologist V. Goldschmidt (Goldschmidt, 1917). Aluminium-production based on acid leaching of anorthosite was his innovative idea, and the easily soluble calcic Sogn anorthosites were proved to be well suited for an acid process. Goldschmidt mapped parts of the large anorthosite massifs along the Sognefjord in the period 1916-19. During WW2 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 tonnes of rock was produced before sabotage ended the work in 1945.

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 tonnes of good soluble anorthosite with minor amounts of mafic minerals were located and a possible Norwegian alternative to imported bauxite was verified. The project, however, was terminated, as the concept was not found to be commercially compatible with existing bauxite based alumina production (Braaten, 1991).

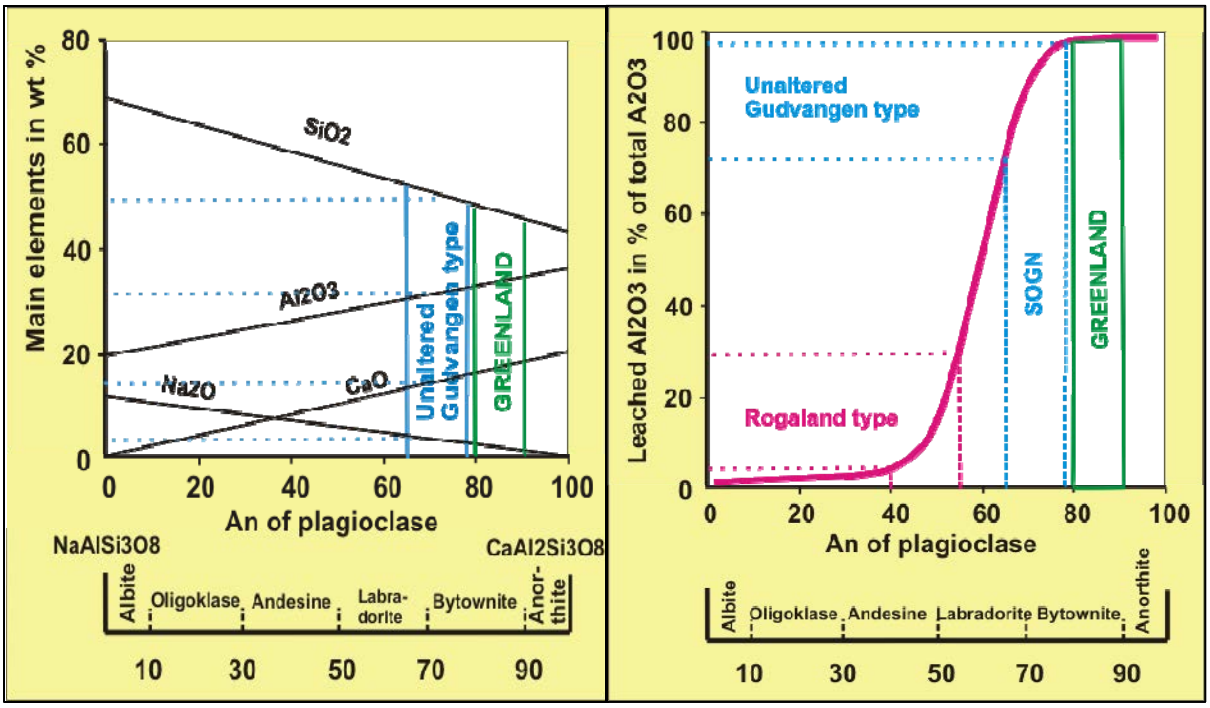


Figure 28 Chemical composition of plagioclase (left) and solubility of plagioclase (right).

Late last century the Gudvangen anorthosite was the main target for companies that evaluated the rock as raw material in applications such 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 been 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 minerals production. Smaller deposits of Fe-Ni-Cu-sulphides were also exploited at the end of the 19^{th} century. In RAP more recent mappings have localized ilmenite bodies that also contain interesting grades of apatite and vanadium (Schiellerup et al 2003).

The geological mapping of the Sogn anorthosites revealed various anorthositic rocks, and 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/large grained anorthosite
  b. Spotted anorthosite
  c. Dark redbrown even grained anorthosite
  d. Grey middle-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.

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. The plagioclase is of varying chemical composition in a solid solution series of its end members albite $NaAlSi_3O_8$ and anorthite $CaAl_2Si_2O_8$.

During his surveys in Sogn in 1917 Goldschmidt pointed out the importance of the An content for acid solubility (Goldschmidt, 1917) 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 28).

The conclusion is that below An 40-50 the plagioclase is hardly soluble, 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 this:

Albite contains Al:Si in a ratio 1:3 and the acid attacking Al-O and Ca-O bondings is not able to penetrate below 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 high-soluble plagioclase in this area. (Bøggild was a known Danish geologist with much fieldwork in 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. But 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 by clogging of filters. On the other hand silica-gel is a valuable product if the quality is good.

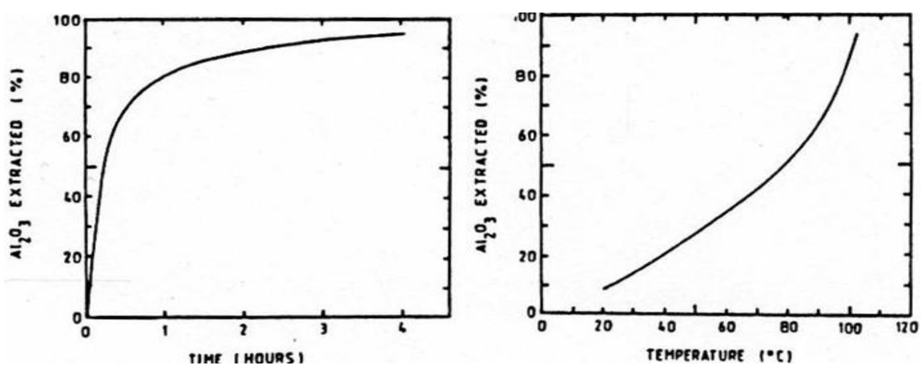


Figure 29 Solubility in relation to time and temperature. (Gjelsvik 1980)

The anorthosites of Greenland are in the range of An_{60-90}, which suits the industrial process described above well. 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 better in solubility than the best Norwegian ones in Sogn and Voss – averaging An_{75}.

Figure 29 illustrates the influence leach time and temperature has on the anorthosite solubility. Both graphs are based on good soluble Sogn anorthosite. High temperature is vital for good extraction. The rate of acid intrusion of 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.

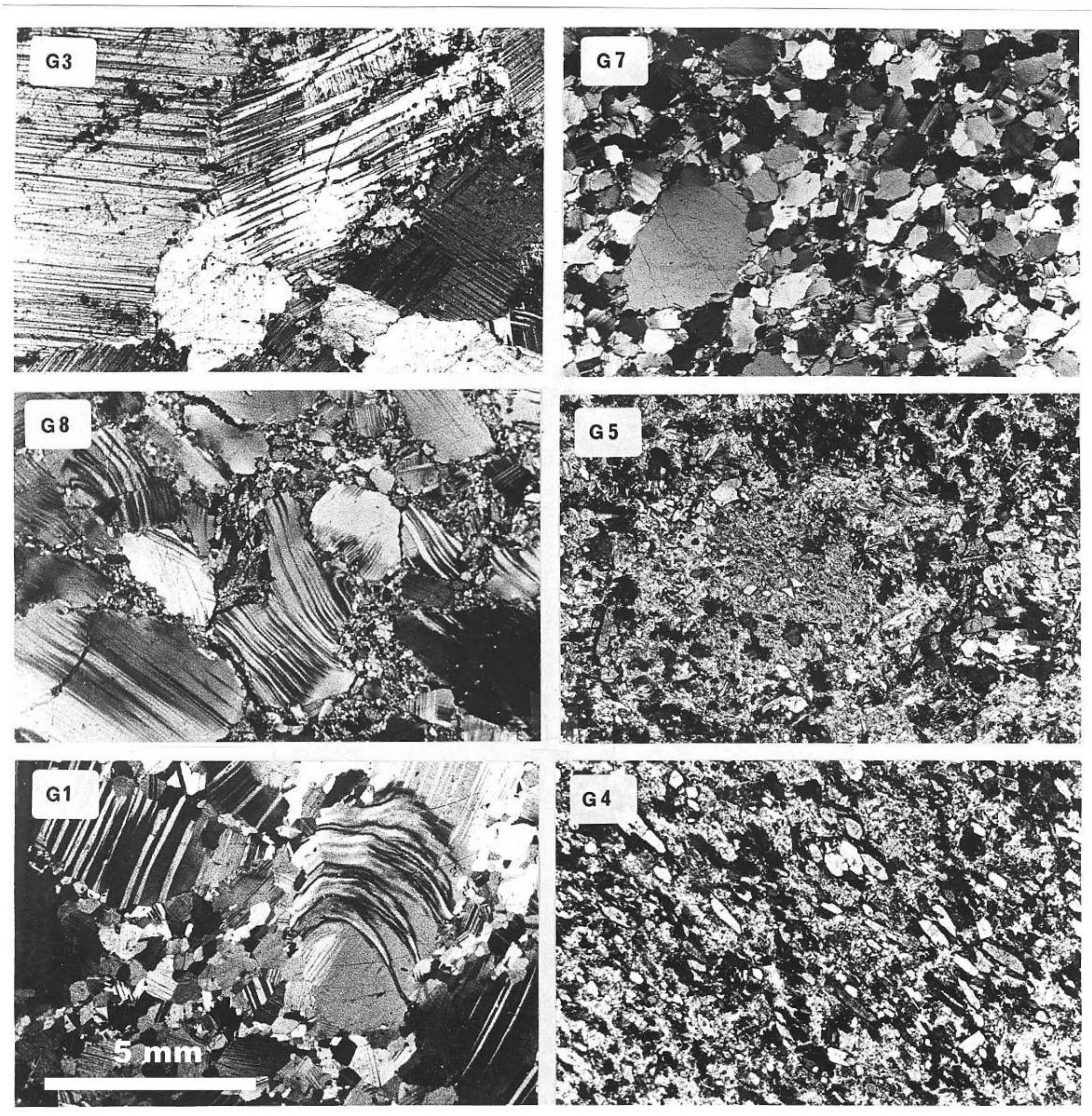


Figure 30 Stages in alteration of bytownite to epodote-oligoclase in anorthosites Gudvangen-Stalheim area. (Bryhni et al, 1983)

Alteration/Saussuritization

Easily soluble high calcium plagioclase can 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 near to unchanged but the plagioclase chemistry is much changed and the resulting rock is almost non-soluble. Figure 30 gives a visual impression of the gradual decomposition of the larger plagioclase grains in a saussuritization process where the rims along primary large grains are altered to fine grained low An plagioclase. Tensional bending of twinning lamellae is shown (Figure 30, G8) 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/chlinozoisite, chlorite and sericite/paragonite (Figure 30, G4).

Honeycomb texture

The first visible sign of a beginning alteration is sometimes clearly visible at weathered surfaces of anorthosite in the field, reflecting the first stage of alteration where only the rims along primary large grains are altered. When thus 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 lies along grain boundaries of larger soluble grains. This results in a honeycomb-like texture on weathered surface as illustrated in Figure 31. In an industrial leach-process it is the volume % of soluble and non-soluble plagioclase that is affecting the total solubility of a sample or a deposit, and when only rims around large grains are non- or low soluble then the average solubility will remain relatively high. This is also the case where alteration is concentrated in thin lines or zones.

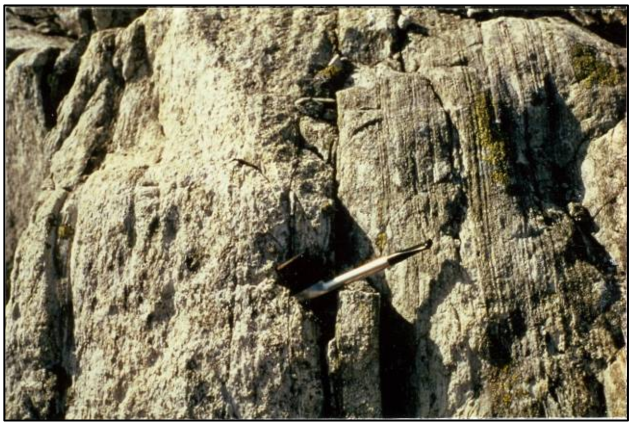


Figure 31 ”Gneissified” zone in Gudvangen anorthosite.

Tectonic zones – “gneissification”

When tectonic movements increase the foliation increases and gradually gneiss zones will be produced. Saussuritization of the anorthosite then takes place and acid solubility is adversely affected. In the Sogn investigations such zones were found to be very local or they might have a larger extension. In the drill cores of the Anortal project various such tectonic zones were cross-cut and the chemical analyses showed distinctly lowered solubility than the surrounding fresh anorthosites. The Anortal-drillings were done in predominantly fresh anorthosite, and the - altered zones cut by drill holes were only some meters thick. The regional geological mappings of the Sogn anorthosites have 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 31). This altered zone has produced a white anorthosite with the typical non-soluble albitic plagioclase, epidote, clinozoisite and micas as dominant minerals (Figure 30).

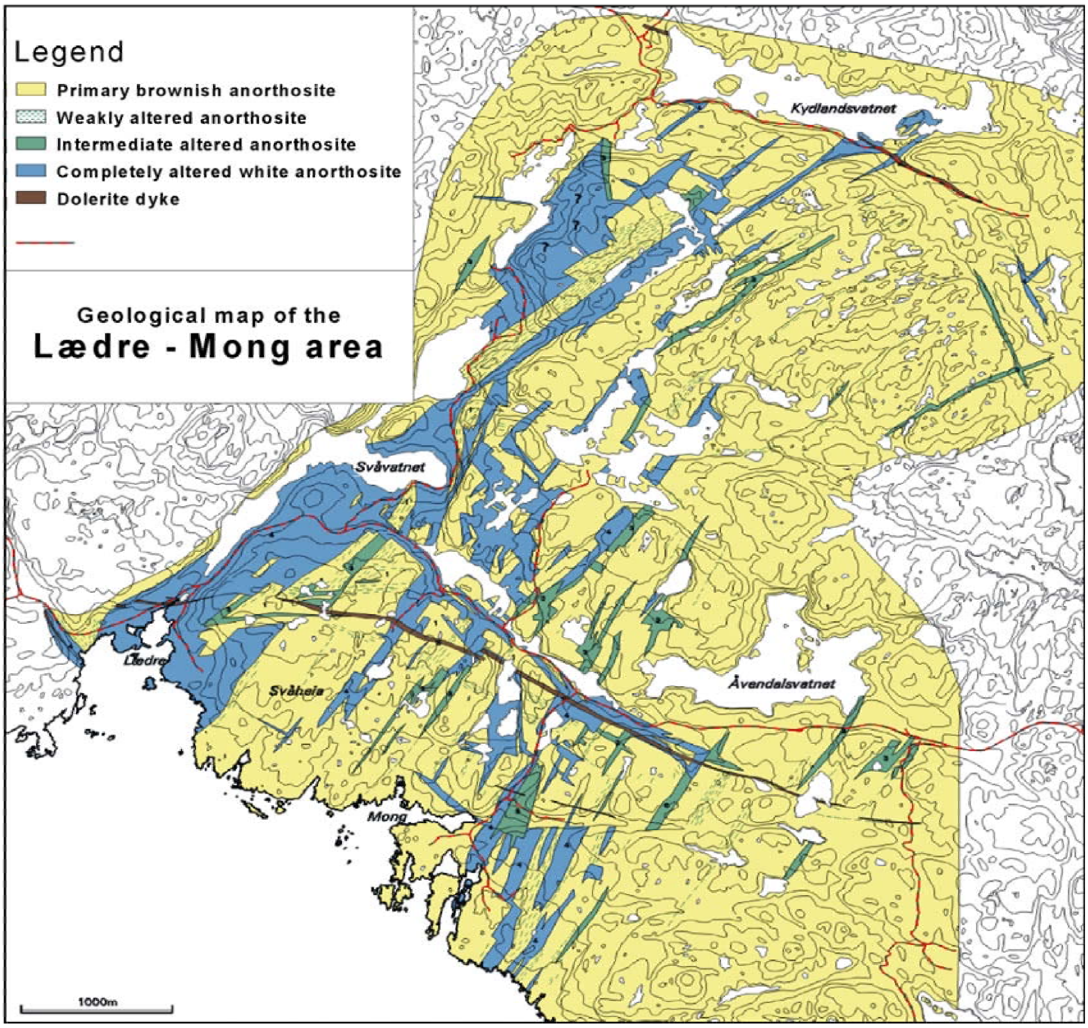


Figure 32 Geological map of altered zones in the Rogaland anorthosite.

Hydrothermally altered zones

Mapping of the anorthosites in the Rogaland province has shown that the saussuritization can take place also by 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 dominating NE-SW direction, but locally up to 100 m wide subordinate crossing NW-SE zones occur as shown in Figure 32. These altered zones prove to have given the anorthosite improved mechanical strength and this rock is attractive especially for export for white road aggregate. The whitest qualities are also used as fillers.

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 rocktypes inside the mining area in Nærøydalen.

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 mafics are commonly scattered in spots and mottles, more or less elongated according to foliation.

Inclusions and colour of the anorthosite.

The colour of the unaltered Sogn anorthosite might vary from almost white, through light grey, dark violet, brick-red and dark redbrown. The dark violet and reddish colours are due to sub microscopic inclusions of Fe- and/or Fe-Ti-oxides crystallized 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 redbrown anorthosites have the highest An. Various violet shades are a sign of excellent soluble quality in most of the better Sogn areas.

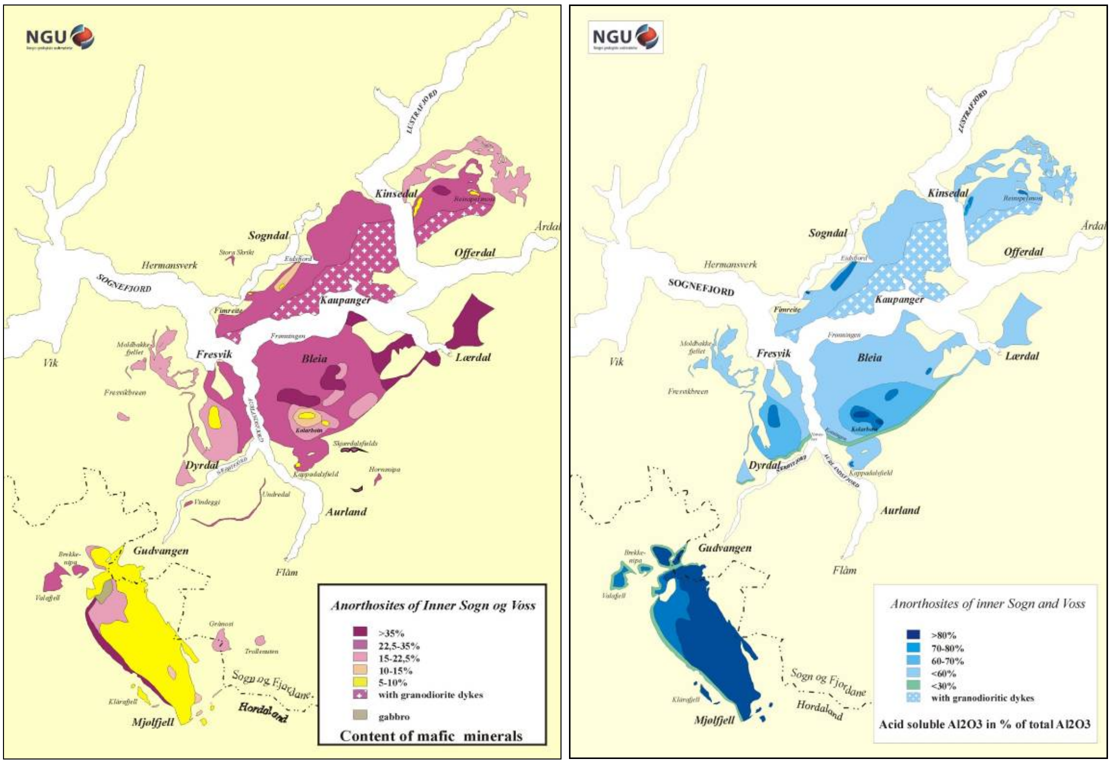


Figure 33 Variations in solubility and content of dark minerals in the Sogn anorthosite province (Wanvik, 2000).

The Rogaland anorthosites are brownish to violet brownish-beige. When altered anorthosites in general becomes white no matter what the primary colour of the plagioclase is.
One thing to be noted is however that most of the primary plagioclase has many inclusions of small (< 0.02mm) euhedral epidote-grains that follows 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 leach process.

The majority of fresh Sogn anorthosites are medium to coarse-grained with grain sizes 2-5 mm. In processing this is advantageous since the main leaching tests in pilot scale have been with fraction 0.3-3.0 mm giving very good liberation of the separate mineral grains. The Rogaland anorthosite is large grained (1-3 cm) with phenocrysts up to several centimetres.

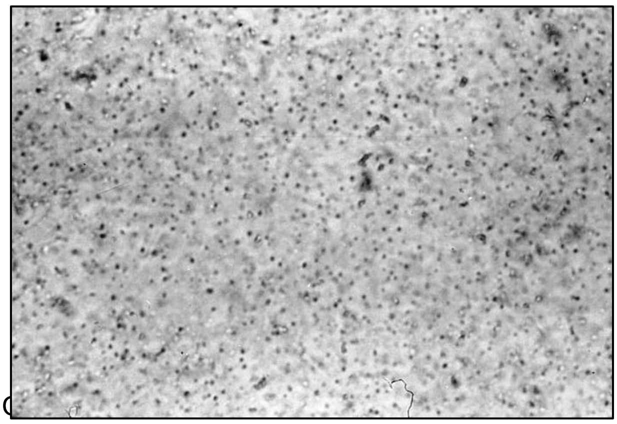


Figure 34 Fe-oxides in primary plagioclase.

Longest side 1.6 mm

Solubility of other minerals

Depending upon which kind of industrial processing 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 vary and it seems that it is the more magnetic susceptible minerals as biotite and chlorite that is solvable while the non-magnetics as epidotes and zoisites are hardly solvable. With magnetic separation only minor amounts of Fe and Mg will then enter into solution.

Field procedures

In the Anortal project the main aim was to localize a deposit with a minimum volume of 100 mil tons of good soluble anorthosite for a 20 years mining period of 5 million tons a year. The project was divided into three major steps.

The first step was to locate 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 33). After initial surveys the most geologically and geographically suitable areas with good soluble anorthosite were pinpointed close to Gudvangen (the bottom left body in Figure 33).

Second step was to find areas with <u>low content of non-plagioclase minerals</u>. These were mainly mafic minerals, easy to distinguish from the lighter plagioclase in the field, and most areas had too high contents of mafic minerals (Figure 33). The Gudvangen-massif though proved to have large areas with acceptable mafic contents. During detailed fieldwork the anorthosite was subdivided in several subclasses dependent on content of dark minerals. In the best areas the contents of dark minerals was below 1.5 % and average was below 3%.

Third step then was to exclude areas with <u>too high representation of dykes of other rocks</u>. The dominating gabbroic and amphibolitic dikes occur partly in swarms and such areas are not attractive. The area with the least dikes was chosen for further <u>mapping, sampling and a core drilling program.</u> The required minimum100 mill tons of good anorthosite for open pit mining was then confirmed at two locations in late 1970'ies. Today open quarrying is not allowed in this area that in the meantime has become both a protected landscape area and a World Heritage area.

Feldspars are normally not significantly weathered in the Norwegian climate, and when doing reconnaissance and more detailed evaluations of the various zones and areas of the anorthosites ordinary geology hammer or preferably a sledge was proper to use 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 tied while preparing the samples. Using a sledge made it also possible to take samples even on more rounded surfaces. When sampling for representative chemical analyses during detailed mapping we collected several smaller samples from each local area and put them all into one bag – some kg per sample. The size of each local area is somewhat dependent on the homogeneity of the anorthosite. During the initial regional mapping phase we sampled mostly single samples to restrict the weight.

At an early stage a small portable core drilling equipment 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-sampling will ordinarily give more flexibility and much higher speed in a sampling situation. For larger samples to processing tests dynamite was used and the diamond drilling programs were executed with heavy equipment giving 32 mm cores. Length of core holes were 100 to 250 m In the Anortal-project a total of 3000 m cores were drilled. In order to do good a detailed geological mapping, topographical maps were constructed in scale 1:2000 as a supplement to the available topographic maps and aerial photographs. One might mention that this was long time prior to GPS technology was available for such projects.

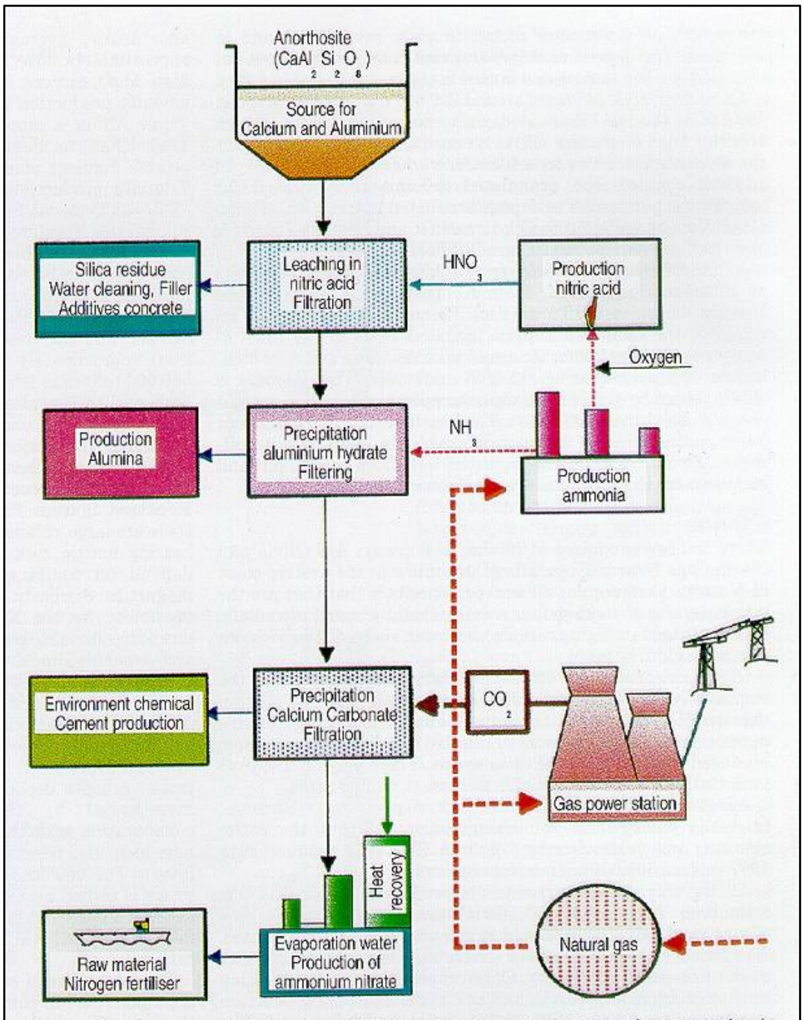
Industrial processing and quality specifications

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

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

The high aluminium content of the Sogn (and Greenland) anorthosites is the major pro compared to most anorthosite bodies worldwide, and the 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, 1991) HCl was found to be best suitable and the pilot scale processing done by the Institute of Energy (IFE) proved to be very successful with a total of 4 tonnes of good quality aluminium-oxide produced (Gjelsvik, 1980). The process was though not commercially compatible with the ordinary bauxite-based alumina production.



Institute for Energy and Technology (IFE) has developed a concept where anorthosite is the raw material for the production of silica, alumina and PCC. Source: IFE

Figure 35

Modified process incorporating CO_2.

A later development at the same institute (Andresen, 2006) 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 as calcium carbonate, silica-residue and ammonium nitrate (Figure 35). 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.

Attractive products as calcium carbonate, silica-residue and ammonium nitrate is then produced (Figure 35, Table 15), making a close to full use of all components of the anorthosite. So far this environmentally well-profiled alternative has proven technically workable but important process and product developments still remains to properly access 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 a somewhat deterrent to established industrial companies, but potential by-products such as Precipitated Calcium Carbonate (PCC) and precipitated silica in addition to the alumina gives a solid basis for future expectations in commercial realization of this CO_2-integrated concept. A future also dependent on market prices of carbon-credits.

Table 16 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**	**Al_2O_3**	**$CaCO_3$**	**CO_2**
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.

By Alkaline leaching of the anorthosite it is also possible to extract the aluminium-component, but such processes are more costly and more energy-consuming and have not been further considered in Norway.

Leach processing gives a highly porous silica residue as one of the products, and this has proven to have several potential applications (Table 17). Some of these are tentatively tested and evaluated on material from the above mentioned processes. All leaching processes require a soluble calcic anorthosite, and low contents of mafic minerals is advantageous.

Processes that include some melting of the raw material have been tested for several purposes. 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 tiles and sanitary porcelain products.

Two other possible applications (developed in Norway) in the metallurgical arena that has 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 of aluminium electrolytic cells in the aluminium industry. Testing is as raw material in an alternative new direct electrical melting method of producing both aluminium and solar grade silicon.

Table 17 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

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 some additional grinding to the former uses in toothpaste and scouring powder.

Table 18 Commercial and potential uses of anorthosite**.** *Norwegian operative or tested uses in italics*. (Wanvik 2000)

Processing	Products	Uses	Specifics
Physical.	Plagioclase grains with	Aggregates	***Light coloured road surfaces, gardens***
(dry or wet mineral	crystal structure intact	Building materials	***Concrete elements, dimension stone, industrial floors***
processing)	(White altered variety most	Abrasives	***Scouring powder, toothpaste***, sand blast-

	attractive)		ing
		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***		

Comparison of anorthosites in Geenland

The 12 anorthosite complexes briefly described above all belong to the calcic Archaean type anorthosites, but the chemical composition varies considerably, both among the different complexes and within the complexes. Even within the samples there is a considerable variation in the plagioclase composition. As anorthosite is almost monomineralic, whole rock analysis will give an average plagioclase composition. However, when e.g. Figure 36 is compared to Figure 37 and Figure 38 to Figure 39 the scatter in whole rock composition is larger than the scatter in mineral chemistry.

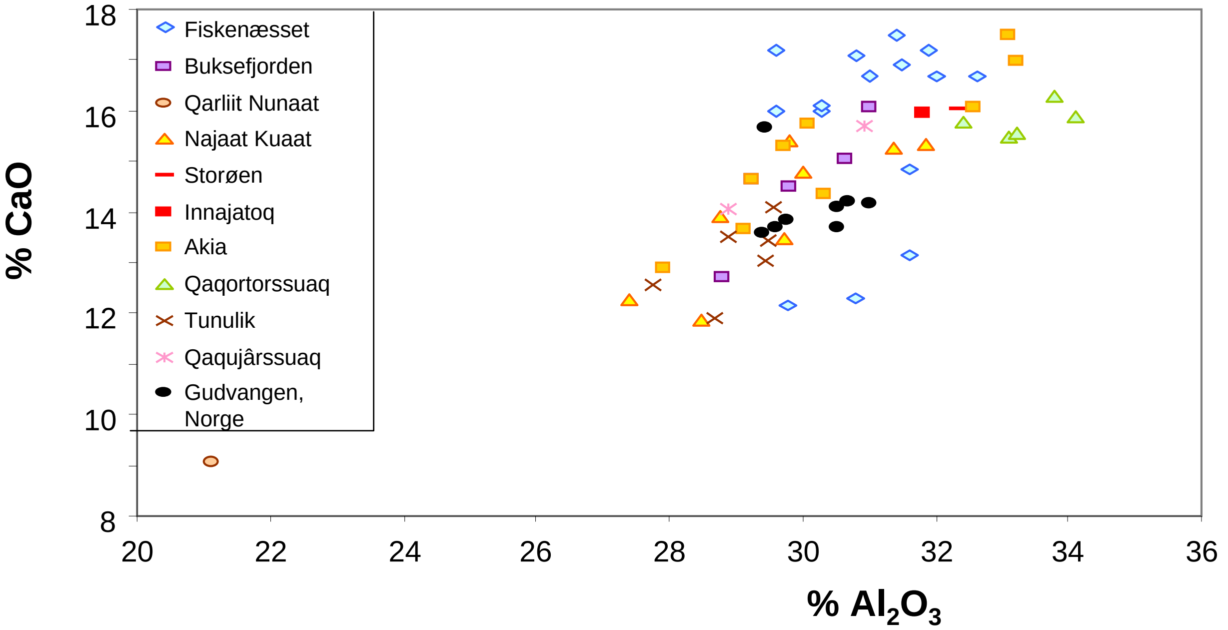


Figure 36 CaO versus Al_2O_3 in whole rock analyses of anorthosites.

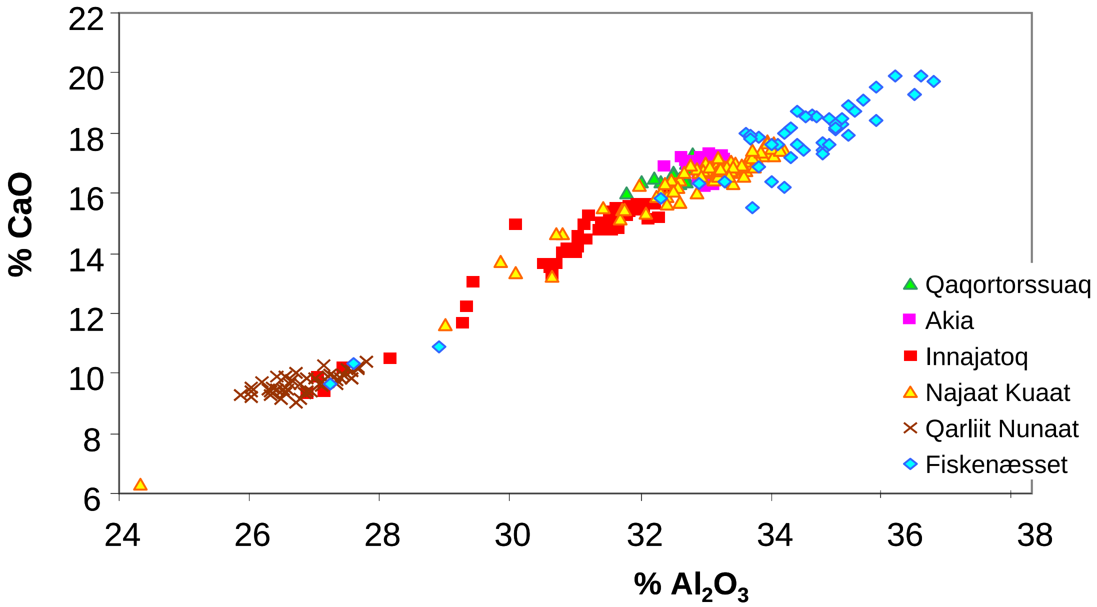


Figure 37 CaO versus Al_2O_3 in microprobe analyses of anorthosites.

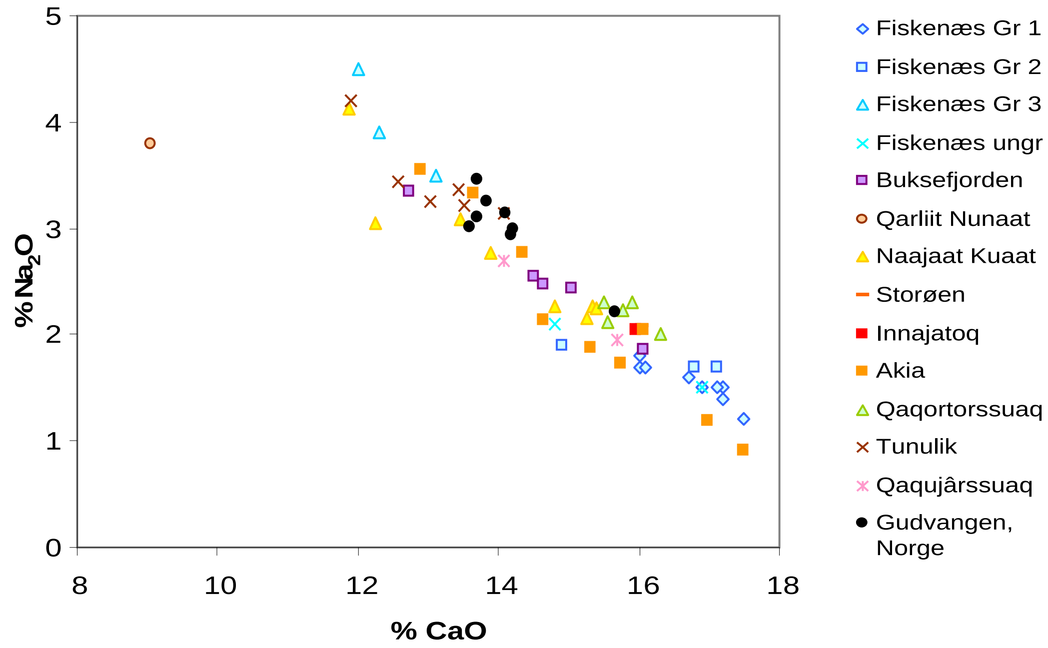


Figure 38 Na_2O versus CaO in whole rock analyses of anorthosites.

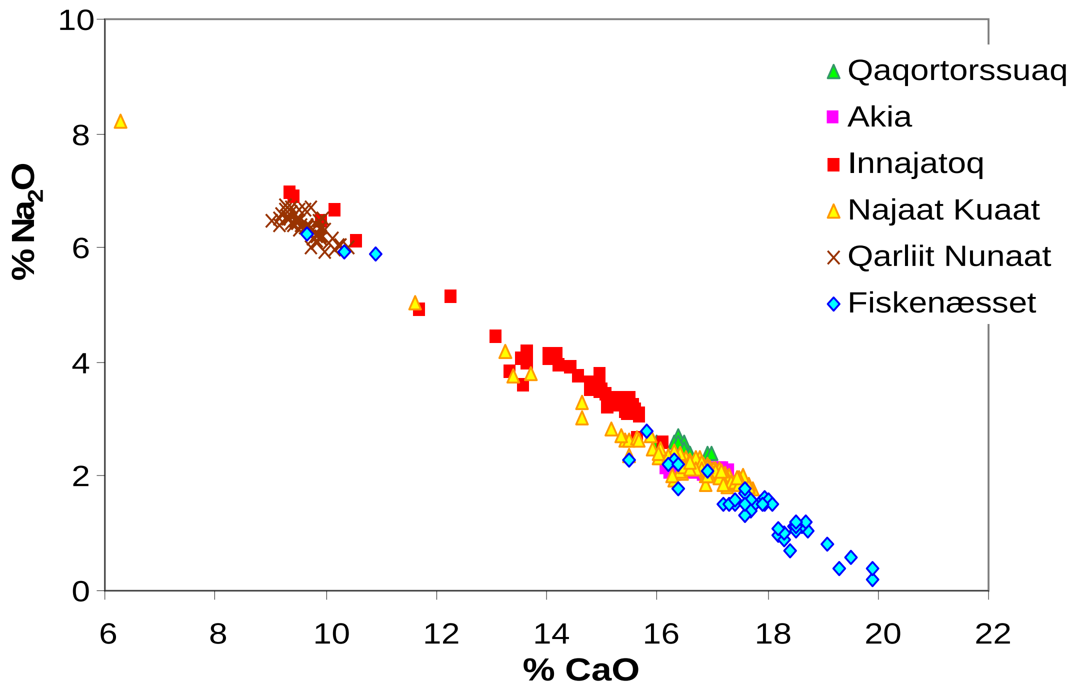


Figure 39 Na_2O versus CaO in microprobe analyses of anorthosites.

As can be seen on Figure 38 the anorthosite in Fiskenæsset are the most calcic found in Greenland. This is backed by the observation that CaO is high in these rocks as well (Figure 36). However, there is an indication by the whole rock analysis that some of the anorthosites from Nordlandet also will have very calcic plagioclase. This has however not been measured. Further, it can be stated that most of the Greenlandic anorthosites are more calcic that their Norwegian counterparts.

The anorthosite bodies Inner Sogn-Voss area of Western Norway by the Sognefjord have a labradorite-bytownite plagioclase composition with anorthite content of 60-78%.

Table 18 Average composition of Greenland anorthosite

	N	Al2O3	CaO	Fe2O3	Na2O	CIPW % plag	CIPW % An
Fiskenæsset, Group 1	13	30,6	16,3	2,5	1,8	90,1	83,8
Fiskenæsset, Group 2	3	32,5	16,3	1,9	1,8	94,1	83,6
Fiskenæsset, Group 3	3	30,5	12,5	1,5	4,0	92,4	65,7
Buksefjorden	6	29,3	14,1	1,5	2,2	90,7	73,7
Ivisartoq	6	29,8	14,7	3,0	2,6	91,1	75,2
Qarliit Nuaat	1	28,5	11,9	0,9	4,1	93,0	61,0
Inajatoq	1	31,8	16,0	1,5	2,0	91,6	84,4
Naajat Kuuat	7	28,9	13,6	1,8	2,5	88,7	72,9
Storøen	1	32,3	16,0	2,1	0,6	96,6	81,3
Akia (Nordlandet)	9	30,6	15,2	1,8	2,2	91,4	79,6
Qaqortorssuaq	3	33,6	15,8	0,9	2,2	94,1	82,6
Tunulik	5	28,9	12,9	1	3,5	91,5	67,1
Qaqujarssuaq	2	29,9	14,9	1,2	1,7	91,6	77,3
Gudvangen (Norge)	8	30,1	14,1	0,8	2,9	94,6	72,0

Future studies, recommendations for further investigations of selected anorthosites linked to the limitations of the economically most profitable techniques and to the removal of CO2. Which complexes should be looked at. Nordlandet, Fiskenaesset, Innajatoq and Qaqortorssuaq...more? The Naajat Kuuat body is nicely "massive" in the centre but the infra-structure to transport rock down to the fjord on that site will be problematic.
The homogeneity and low content of mafic minerals makes the Innajatoq interesting. A fracture distribution study should be recommended - to estimate the more altered volumes of the total body.

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