Anorthosites in Greenland: a possible raw material for aluminium?

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The famous Swiss-born, Norwegian geologist and geochemist Victor Goldschmidt suggested that anorthosite could be used as a source of aluminium replacing bauxite, and acid leaching of the anorthosite was his innovative idea. Anorthosite is a rock type consisting of more than 90% plagioclase which is an acid-soluble, aluminium-rich silicate mineral occurring in basement rocks of both Norway and Greenland (Fig. 1). Experiments conducted in Norway during the century after Goldschmidt's initial idea showed that it is technically possible to use anorthosite as a raw material in the production of aluminium metal. Goldschmidt mapped parts of the large anorthosite massifs along Sognefjord in the period 1916–1919. During the Second World War, sampling and core drilling were conducted in Norway, and an anorthosite mine was opened by Norsk Hydro where up to 400 men were employed and some 15 000 tonnes of rock were quarried before sabotage ended the work in 1945. There was renewed interest in anorthosite as an alternative raw material for aluminium in Norway in the years 1976–1982, but experiments conducted in this period did not lead to an economically viable concept. Recent developments at the Institute for Energy Technology in Norway have led to the discovery of a more promising process based on nitric acid that can yield additional products such as Precipitated Calcium Carbonate (PCC) for the paper industry, amorphous silica and ammonium nitrate fertiliser. The process can also be used as a sink for CO_2 by taking CO_2 from, for example, a power plant and binding it to PCC.

Solubility as a function of mineral chemistry

The mineral plagioclase covers a range of compositions from albite ($NaAlSi_3O_8$) to anorthite ($CaAl_2Si_2O_8$) and forms a solid solution series. The solubility of plagioclase, and therefore of anorthosite, increases with the calcium content, expressed as the anorthite content or An% in the plagioclase (Fig. 2). The higher solubility of the calcium-rich plagioclase makes it more attractive as a source of aluminium, as does the content of aluminium which increases with the anorthite content (calcium content; Fig. 2). Anorthosite bodies in the inner Sognefjord–Voss area in western Norway have a calcium-rich plagioclase composition (Fig. 2) with an anorthite content of 65–78%. The solubility and aluminium content determine the quality of anorthosite as a raw material for aluminium production. To provide an overview of

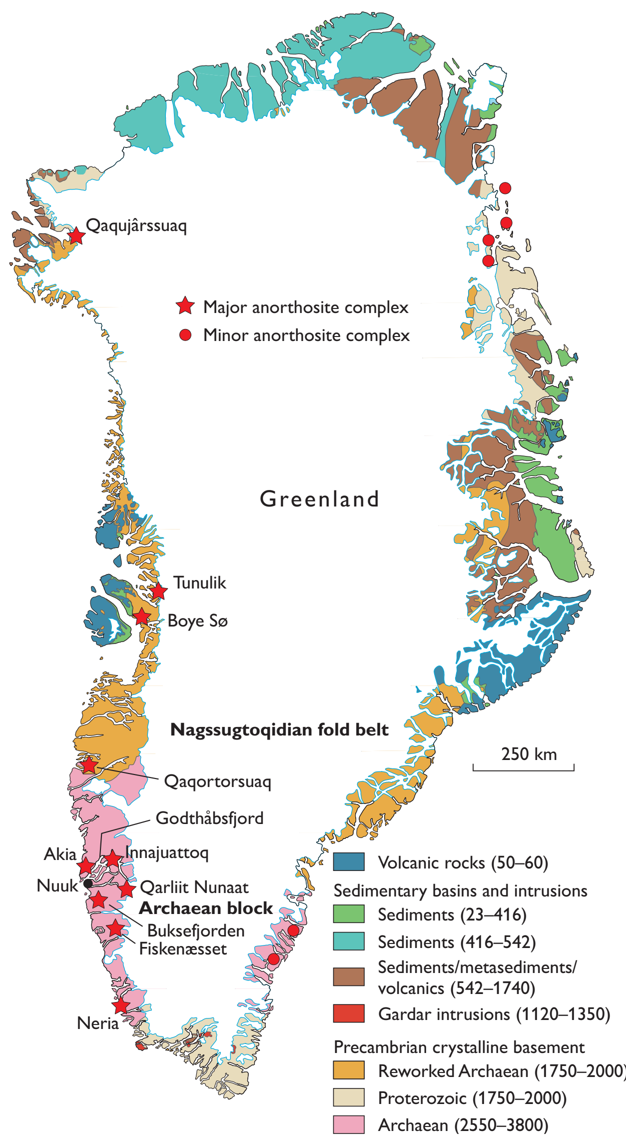

Fig. 1. Simplified geological map of Greenland showing anorthosite occurrences. Ages in million years.

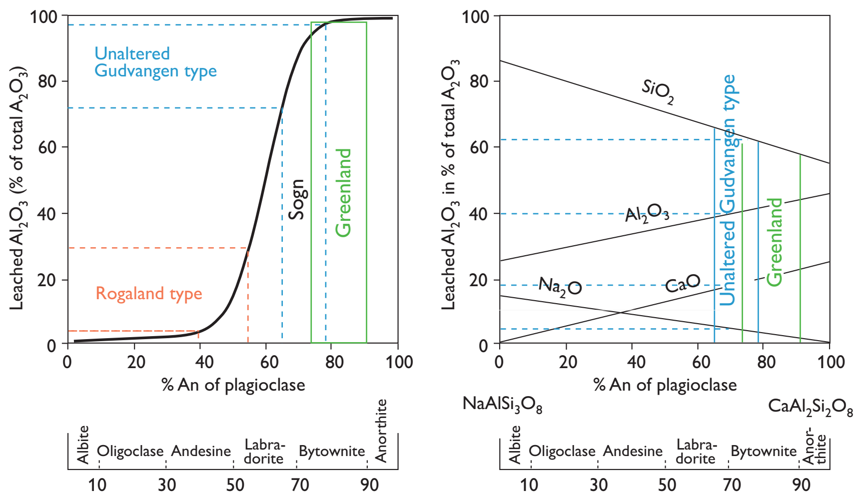

Fig. 2. Chemical composition (left) and solubility (right) of plagioclase. Modified from Wanvik (2000). Gudvangen, Rogaland and Sogn are anorthosite occurrences in Norway. Greenland is based on an average from Table 1.

the variation in these parameters and accordingly the value of anorthosite as a potential raw material in aluminium production, the Geological Survey of Denmark and Greenland conducted a survey of the compositional variation of anorthosite complexes in Greenland.

Anorthosites in Greenland

Anorthosite rock bodies are found in Archaean basement rocks in most parts of Greenland and constitute up to 5% of the bedrock in a region. They are easy to recognise in the field because of their very light weathering colour which also makes the rock very useful as a structural marker when mapping in deformed terranes. Anorthosite can be divided into several types including 'Archaean calcic anorthosite' (Ashwal 1993). The calcium content in the plagioclase of 'Archaean calcic anorthosite' is high (75–90% An). This feature distinguishes Archaean anorthosite from, for example, the 'Proterozoic (massif) type anorthosite' with 35–60% An. So far, only the Archaean type of anorthosite has been described from Greenland.

The Archaean anorthosite occurrences in Greenland are generally deformed and metamorphosed to such an extent that their genetic relationships are difficult to reveal. They often occur as decimetre- to metre-sized pods and inclusions in the country gneiss. However, there are a number of places where larger bodies of anorthosites are found with preserved primary textures and relationships. The most prominent occurrence is the Fiskenæsset complex consisting of anorthosite, leucogabbro, gabbro and ultramafic rocks. Here it has been demonstrated that anorthosite forms parts of large intrusions of basaltic composition and formed as cumulates by crystal fractionation (Windley *et al.* 1973; Myers 1975; Windley & Garde 2009).

Table 1. Average Al_2O_3, CaO, Fe_2O_3 and Na_2O compositions of anorthosites calculated from whole-rock analytical data

	N lat.	W long.	No of analyses	Al_2O_3	CaO	Fe_2O_3	Na_2O	CIPW % plag*	CIPW % An*
Fiskenæsset group 1†	63°15′	50°00′	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	63°55′	51°20′	6	29.3	14.1	1.5	2.2	90.7	73.7
Qarliit Nunaat (Godthåbsfjord)	64°04′	49°45′	1	28.5	11.9	0.9	4.1	93.0	61.0
Naajat Kuuat (Godthåbsfjord)	64°10′	50°03′	7	28.9	13.6	1.8	2.5	88.7	72.9
Storø (Godthåbsfjord)	64°23′	51°07′	1	32.3	16.0	0.6	2.1	96.6	81.3
Akia (Godthåbsfjord)	64°30′	52°06′	9	30.6	15.2	1.8	2.2	91.4	79.6
Ivisaartoq (Godthåbsfjord)	64°44′	49°42′	6	29.8	14.7	3.0	2.6	91.1	75.2
Innajuattoq (Godthåbsfjord)	64°45′	50°40′	1	31.8	16.0	1.5	2.0	91.6	84.4
Qaqortorsuaq	66°35′	52°12′	3	33.6	15.8	0.9	2.2	94.1	82.6
Tunulik	70°03′	51°15′	5	28.9	12.9	1.0	3.5	91.5	67.1
Qaqujârssuaq	77°35′	64°45′	2	29.9	14.9	1.2	1.7	91.6	77.3
Gudvangen (Norway)			8	30.1	14.1	0.8	2.9	94.6	72.0

* % plagioclase in rock and % An in plagioclase are based on CIPW norm calculations. † Fiskenæsset is grouped on the basis of its rare-earth element patterns following Polat *et al.* (2009).

Fig. 3. **A**: The anorthosite at Innajuattoq in the Archaean block northwest of Nuuk. The mountain is 1206 m high, and the cliff section is *c.* 1100 m high. **B**: Close-up view; length of hammer handle *c.* 60 cm.

The primary relationship to the surrounding rocks is often obscured by tectonic activity or intrusive contacts to younger granitoids. All the anorthosites studied here are assumed to belong to the calcic Archaean type but their composition varies, (1) among the different complexes, (2) within the complexes as a function of the stratigraphical position and (3) within the mineral grain – from core to rim, often due to recrystallisation during metamorphism.

Around 12 anorthosite complexes in Greenland have been mapped and described (Fig. 1). The northernmost one is the Qaqujârssuaq anorthosite, which is also the largest single anorthosite mass in Greenland covering *c.* 100 km² of Smithson Bjerge and an unknown area under the Inland Ice (Dawes 2006). It is a *c.* 500 m thick succession composed of *c.* 90% anorthosite, *c.* 10% leucogabbro and <1% gabbro which was emplaced *c.* 2700 Ma ago (Nutman 1984).

The Tunulik anorthosite is located in an area of Archaean rocks deformed and metamorphosed in Palaeoproterozoic time *c.* 1900 Ma ago. Generally, the anorthosite occurs as blocks and pods in the surrounding tonalitic to granodioritic gneisses (Andersen & Pulvertaft 1986). The anorthosite can be traced south to the *c.* 25 km² large Boye Sø anorthosite (Garde & Steenfelt 1989).

The first anorthosite body to be found in Greenland was the anorthosite at Qaqortorsuaq in the *c.* 1900 Ma old Palaeoproterozoic Nagssugtoqidian fold belt (Ellitsgaard-Rasmussen & Mouritsen 1954). This body is very large and the exploration company Kryolitselskabet Øresund A/S estimated that there are *c.* 100 million tonnes of anorthosite per vertical metre in the deposit and the mountain Qaqortorsuaq is *c.* 1300 m high (Gothenborg & Keto 1977). The highest concentration of anorthosite complexes in Greenland is found in the core of the Archaean block around Nuuk (Akia, Innajuattoq, Storø, Najaat Kuuat with Qarliit Nunaat, Nunatuasuk and Ivisaartoq; Fig. 1; Table 1). One of the anorthosite bodies is located at Innajuattoq (Fig. 3).

The Fiskenæsset anorthosite complex is one of the largest and best known Archaean anorthosite complexes worldwide. Parts of the complex have retained an igneous stratigraphy, cumulate textures, layering, grading and channel deposits (Windley *et al.* 1973; Windley & Smith 1974; Windley & Garde 2009; Myers 1975, 1976, 1985), showing that it is a sheet-like, layered basic intrusion. Based on *in*

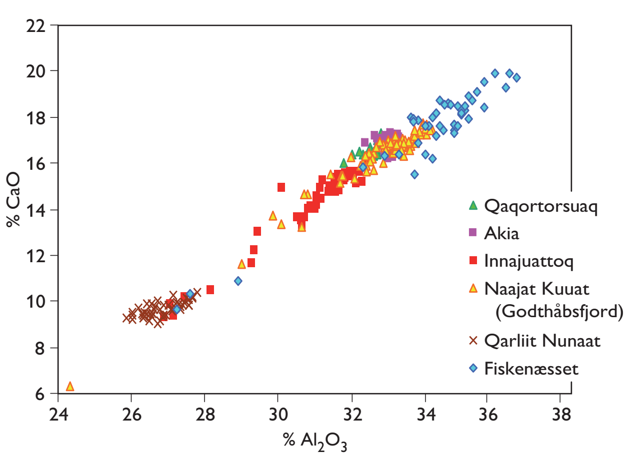

Fig. 4. Microprobe analyses of plagioclase from Greenland anorthosites showing CaO versus Al_2O_3 wt%. The range of plagioclase compositions is due to variations from core to rim in individual grains as well as to variations between different parts of the complexes. The linear relationship between CaO and Al_2O_3 is due to the coupled substitution of albite ($NaAlSi_3O_8$) by anorthite ($CaAl_2Si_2O_8$).

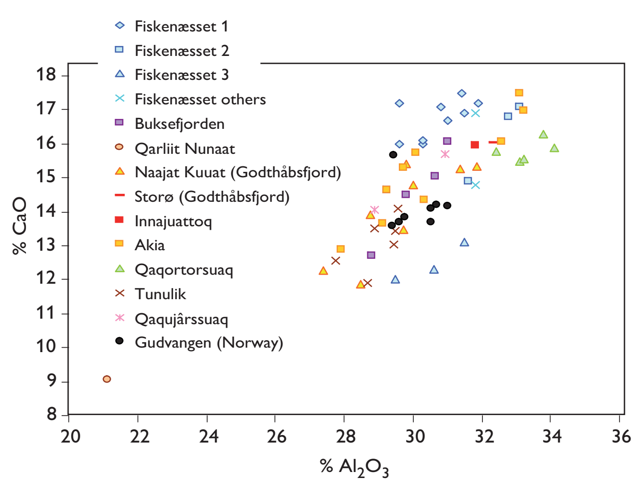

Fig. 5. Whole-rock analyses of anorthosites showing wt% CaO versus wt% Al_2O_3. Anorthosites in Greenland are compared to anorthosites from Gudvangen in Norway. Most of the Greenlandic occurrences have higher CaO content due to higher anorthite content. Hence their plagioclase is rich in both Ca and Al.

situ $^{207}Pb/^{206}Pb$ zircon ages of up to 2950 Ma, Keulen *et al.* (2010) concluded that the intrusion age is *c.* 2970 to 2950 Ma. The anorthosite unit is *c.* 250 m thick (Myers 1985). At localities where the anorthosite is least deformed, it typically appears as megacrystic with 1–10 cm equant, relict igneous 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.

Anorthosite composition

There is a large range of plagioclase compositions among the anorthosite complexes in Greenland (Fig. 4) with the highest content of calcium found in the Fiskenæsset complex. Whole-rock analyses indicate that very calcium-rich plagioclase also occurs in the anorthosite at Akia (Fig. 5; Dymek & Owens 2001).

Most Greenland anorthosite rocks are more calcic than the Norwegian ones and according to the Norwegian experiences should be more soluble and hence more suitable as a raw material for aluminium production. A possible continuation of this project could be to collect samples from anorthosites in Greenland and conduct solubility tests using the Norwegian methods. The most promising occurrence is the Fiskenæsset complex which is the largest anorthosite in Greenland, has the highest bulk rock CaO content and contains the most calcic plagioclase in Greenland. The anorthosites at Akia, Innajuattoq and Qaqortorsuaq contain very calcic plagioclase and low contents of other minerals. These occurrences are located close to the sea and could be targeted in further studies.

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