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GRØNLANDS GEOLOGISKE UNDERSØGELSE

A STUDY OF RADIOACTIVE VEINS
CONTAINING RARE-EARTH MINERALS
IN THE AREA SURROUNDING
THE ILÍMAUSSAQ ALKALINE
INTRUSION IN SOUTH GREENLAND

CONTRIBUTION TO THE MINERALOGY OF ILÍMAUSSAQ,

No. 12

BY

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WITH 9 FIGURES AND 6 TABLES IN THE TEXT
AND 3 PLATES

С РУССКИМ РЕЗЮМЕ

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Abstract

Radioactive veins containing the rare-earth minerals monazite and bastnäsite are found in tension joints in Precambrian sandstone, granite, lavas and dykes on the eastern side of the alkaline Ilímaussaq intrusion in South Greenland. The veins were formed in several phases. First, small cracks were mineralized with hematite, fluorite, quartz and radioactive material. This was followed by emplacement of brown albititic veins in which albite and opaque material predominate, green veins with a high content of aegirine, white albititic veins, carbonate veins and finally quartz veins. All the vein minerals may be coated by a late iron-manganese oxide. Most often the veins are separate, but they may also occur composite. The veins are from a few millimetres to about three metres wide; most commonly they are one to ten centimetres wide.

The radioactivity is mostly due to thorium, but a few veins have a uranium content higher than that of thorium. The thorium content ranges from 60 to 4500 ppm, the uranium from 17 to 1500 ppm. The ratio thorium/uranium ranges from 0.1 to 57.2.

The radioactivity is predominantly connected with pigmentary material, thorite, thorianite, monazite and bastnäsite. Other minerals identified in the vein are aegirine, acmite, albite, arfvedsonite, apatite, biotite, calcite, chlorite, eudialyte, fluorite, hematite, lithium mica, mesodialyte, microcline, neptunite, pyrite, quartz and sphalerite.

The following constants were calculated from X-ray powder diagrams made with a Guinier-Hägg camera.

Bastnäsite: $a_0 = 7.120 \pm 7 \times 10^{-3} \text{ \AA}$; $c_0 = 9.77 \pm 2 \times 10^{-2} \text{ \AA}$; $c_0/a_0 = 1.372$; $V_0 = 428.96 \text{ \AA}^3$.

Monazite: $a_0 = 6.780 \pm 5 \times 10^{-3} \text{ \AA}$; $b_0 = 7.025 \pm 4 \times 10^{-3} \text{ \AA}$; $c_0 = 6.471 \pm 4 \times 10^{-3} \text{ \AA}$; $\beta = 103.35 \pm 7 \times 10^{-2}$; $V_0 = 299.84 \text{ \AA}^3$.

Micro-differential thermal analyses are given for bastnäsite and thorite, thermoluminescence analyses are given for natural bastnäsite and thorite and for artificially γ -radiated bastnäsite. Chemical, X-ray fluorescence and spectrochemical analyses are given for the different vein types. These analyses confirm the petrographical examination which has shown an erratic distribution of the rare-earth and radioactive minerals along and across the veins.

It is suggested that the veins were formed at shallow depth and at low temperature.

РЕЗЮМЕ

Радиоактивные жилы, содержащие редкоземельные минералы монацит и бастнезит, залегают в трещинах растяжения в докембрийских песчаниках, гранитах, лавах и дайках восточной части щелочной интрузии Илимауссак (Ю. Гренландия). Жилы формировались в несколько фаз. Сначала по трещинкам происходило накопление гематита, флюорита, кварца и радиоактивного материала. Затем последовало образование коричневых альбититовых жил с преобладанием альбита и опакowego материала, зеленых жил с высоким содержанием эгирина, белых альбититовых жил, карбонатных жил и, наконец, кварцевых жил. Возможно, что все жильные минералы были покрыты поздними окислами железа и марганца.

Радиоактивность в основном за счет тория, хотя в некоторых жилах содержание урана превышает содержание тория.

Радиоактивность связана в основном с пигментационным материалом, торитом монацитом и бастнезитом. Другие минералы жил – эгирин, акмит, альбит, арфведсоит, апатит, биотит, кальцит, хлорит, эвдиалит, флюорит, гематит, литиевая слюда, микроклин, пирит, кварц и сфалерит.

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I. INTRODUCTION

A study of the radioactive veins in the area surrounding the Ilímaussaq alkaline intrusion in South Greenland was carried out as part of a radiometric survey of a larger area. The area covered by this study is situated on the north-east side of the Ilímaussaq intrusion (61° N; 46° W) on the south-east side of the peninsula between Bredefjord and Tunugdliarfik (plate 2). The field work was first planned as a geiger survey to be made by non-geologists recording the geiger readings on topographic maps. From this survey it was found that the area surrounding the Ilímaussaq intrusion locally has a strong radioactivity. Since the author could only spend a very short time in the field, it was decided to concentrate work on a detailed investigation of a small area in order to obtain an understanding of the mineralization rather than to investigate all the different vein types in the whole area.

The report presented here comprises field investigations, measurements of radioactivity in the field, and laboratory investigations of the collected material. The laboratory work includes petrography and mineralogy combined with autoradiography, differential thermal analyses, thermoluminescence analyses and chemical analyses.

The radioactivity is situated in mineralized fracture zones. In addition a continuous cover of vegetation and extensive areas of glacial deposits make the tracing of the veins difficult. The map (plate 2) shows the uranium-thorium mineralized zones where they are exposed or can be traced by the use of a geiger counter.

Previous work on the veins

LARSEN-BADSE (1959) undertook radiometric measurements in the area in 1958 and collected many of the samples investigated by the author. The map, presented as plate 2, is partly based on his work. OEN (1959) studied the veins in the area around Sitdlisit. Later work has included an autoradiographic examination of thin sections from the area (BUCHWALD *et al.*, 1960). Many of the results presented in this report are based on those of the earlier work.

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II. GEOLOGICAL SETTING OF THE VEINS

The geology of the area has been described by a number of authors (USSING, 1912; WEGMANN, 1938; POULSEN, 1964 and STEWART, 1964), and only a very brief synopsis is given here.

The oldest rocks exposed in the region investigated occur at the north-eastern end of the peninsula (plate 2). They are Precambrian medium to coarse grained granodiorites (the Julianehåb Granite) with many veins of aplite and pegmatite and, in some places, schlieren and lenses of amphibolite.

This basement granodiorite is overlain to the west by a succession of sandstones and lavas belonging to the Precambrian Eriksfjord Formation. In this area the succession has a conglomerate at the base followed by red and white coarse to fine grained sandstones. The whole formation is extensively cut by sills and dykes which locally affect the red sandstone turning it green in colour due to reduction of hematite in the sandstone. The dykes, which are vertical and mostly strike NE—SW, consist of dolerites and trachytes.

To the west of the area described here the Ilimaussaq alkaline intrusion has penetrated the succession of lavas and sandstones and has affected them for a considerable distance from the intrusion. The intrusion is composed dominantly of an agpaitic suite of nepheline syenites in which the last rocks to crystallize (lujavrites and late hydrothermal veins) were accompanied by uranium-thorium mineralization (SØRENSEN, 1962). The agpaitic rocks have an age of 1020 ± 24 m.y. (BRIDGWATER, 1965).

The region is cut by pronounced WNW—ESE fault zones.

The mineralized veins described in this report cut all the rock types mentioned here to the east and outside the Ilimaussaq intrusion.

III. DESCRIPTION OF FIELD RELATIONS

The mineralization occurs as veins which may be as wide as three metres or only fill small cracks and joints of less than one centimetre. They are most commonly from one to ten centimetres wide.

The veins are fine grained, often homogeneous but banded and streaky structure are also present.

The mineralization occurs as zones which can sometimes be followed for several kilometres, but normally they can only be followed for a few metres or decimetres. Where the veins are not visible due to surface cover they can be traced by use of a geiger counter. Plates 2 and 3 list all larger zones of mineralization together with some of the smaller ones.

The veins generally strike NE—SW but some of the veins, especially the thinner ones, may locally deviate considerably from this direction. Most of the veins are vertical but some, especially the quartz veins, may deviate from the vertical.

The veins cut all the country rocks: granite, sandstone, lava and dykes. They may have inclusions of these rocks, especially of the sandstone. The inclusions which are more or less elongated have their long direction orientated parallel to the strike of the veins.

Horizontal and vertical joints in the sandstone are not displaced along the veins but inclined mineralized joints are displaced by a few centimetres.

The stratification of the sandstones is generally not affected by the veins but bedding planes in the sandstone can be turned upwards on both sides of the vein, or turned downwards at another part of the same vein, or one side may be turned upwards and the other downwards. This flexuring of the bedding is not accompanied by any significant fracturing of the wall rock so that it seems to be a plastic deformation presumably contemporaneous with the recrystallization of the sandstone to a green, quartzitic rock.

OEN (1959) explained the variability of the flexuring of the bedding planes in the sandstone as due to slight differential movement of blocks of sandstone in the zone.

From the foregoing it is concluded that the veins have not been formed in fault or shear zones but in zones of tension joints.

Types of mineralization

The following types of mineralization have been recognized, listed from the oldest to the youngest:

- a) Small cracks and joints mineralized with hematite, fluorite, quartz and radioactive material.
- b) Brown albititic veins in which albite and opaque minerals predominate.
- c) Green veins with a high content of ægirine.
- d) White albititic veins only consisting of albite.
- e) Carbonate veins only consisting of calcite.
- f) Quartz veins only consisting of quartz.

In addition to these vein types there are veins which are composed of material from two or more of the vein types. They are described as

- g) Composite veins.

All the veins mentioned may be covered by a late film of black iron-manganese oxides.

a) Mineralized cracks

Cracks and joints in the country rocks, especially in the sandstone, often are coated with hematite and dark brown to black manganese-iron oxides. Besides, most of the cracks are more or less ramified with discontinuous stringers of quartz. Other cracks are filled with quartz while pyrite, fluorite and chlorite are less widespread.

The fillings are often not complete but there are voids with crystals of quartz. Idiomorphic quartz may also grow on the walls of the cracks. The rocks in these zones are often stained with a black coating of iron-manganese oxide. Radioactivity is connected with the iron-manganese oxides and with pyrite, probably due to adsorption of uranium (see p. 27).

The mineralized cracks most often strike NE-SW and are vertical but they may strike E-W, N-S or coincide with the subhorizontal bedding planes in the sandstone. Usually the mineralized cracks are isolated, but sometimes they form zones of closely spaced joints and cracks. These zones are from less than one centimetre to about two metres wide.

This type of mineralization is found all over the area, but is most common along the shore between Sitdlisit and Nûgârssuk where the sandstone is cleaved by a network of vertical joints striking E-W, NE-SW and N-S giving blocks from a few millimetres to several centimetres wide. The joints are often evenly spaced with a master joint about every ten metres and between these there are two or more smaller joints. The E-W trending joints are those most strongly mineralized.



Fig. 1. Brown albititic vein with veinlets of quartz. The vein is found in sandstone. Mussartût.

b) Brown albititic veins

These veins are brown, sometimes with stringers or bands of dark brown to black iron oxides in a brown matrix. The veins may also have discontinuous stringers or veinlets of quartz (fig. 1). In places there is a dark brown to black coating of iron-manganese oxide.

The veins of this group are from less than one centimetre to about two metres wide with an average about 5 to 10 cm.

Fragments of the country rocks of irregular shape and different size occur in the veins giving them a spotted appearance. This is particularly frequent where the veins cut sandstone.

The veins often occur singly with hundreds of metres between each other but may also occur in zones consisting of several thin veins a few centimetres apart.

The mineralization of this vein type is best studied approximately 1 km west of Sitdlisit where a brown albititic vein cuts the sandstone.



Fig. 2. A thin green vein in sandstone 8 km SW of Mussartût.

The vein is ca. 2 m wide, vertical and has a strike of 050° . The colour is brown with black discontinuous stringers of hematitic material and white stringers of quartz. Quartz is also found as veinlets cutting the brown vein. Both the black and the white stringers are generally parallel to the vein direction although some may deviate in direction. The stringers are from less than one millimetre to a few millimetres wide and only a few millimetres to 10 centimetres in length.

The red sandstone is altered to a green quartzitic rock to a depth of 30 cm from the vein. Further away from the vein joints and bedding planes in the sandstone also have a green colour. Adjacent to the altered rock, joints and bedding planes are mineralized with a black material. This mineralization, which is found in the smallest cracks in the green sandstone, is found as inclusions in the outer zones of the veins. This shows that the mineralization of the cracks is earlier than the brown albitic veins. At least some of the hematite stringers in the brown albitic veins may be derived from mineralized cracks.

c) Green veins

The green veins are from about 1 cm to 1 m wide with most of them about 10 cm wide (fig. 2).



Fig. 3. Green vein in sandstone. The vein has a pronounced schistosity. 3 km SW of Mussartût.

Green veins are found all over the area, though most commonly in the southern part. These veins are usually found singly spaced at intervals of a few hundred metres but may also be found in zones of mineralization with two or more veins within a few metres.

The green veins vary widely in appearance. They are fine grained and consist mainly of ægirine and feldspar, in varying proportions. Some of the veins are composed almost entirely of ægirine, others have patches of white material in a green matrix resulting in a streaky appearance, others again have ægirine in a brown matrix. There are in places small (millimetre size) red spots of, or holes after, a thorium mineral (p. 27). Where there are red spots the veins may display a schistosity parallel to the strike of the vein with the ægirine needles either more or less parallel to the strike of the vein or arranged in an irregular way (fig. 3). The veins often have silky, glistening fracture surfaces.

An example of green veins is found approximately 1.5 km north-east of the smallest island of Qeqertat at an altitude of 130 m (plate 2). There are three parallel veins in a dolerite dyke each 0.5 m wide striking 060° and vertical. The veins have a schistosity parallel to the vein direction. This schistosity is bent around inclusions of the dyke. There are 0.5 to 1 mm red grains of a thorium mineral and grey grains of feldspar. The veins also penetrate cracks in the dolerite dyke which has been altered (bleached) for a distance of 10 cm from the vein. Each vein can only be followed for a few metres because of vegetation.

An example of a spotted vein occurs approximately 2 km west of the smallest island of Qeqertat at an altitude of 475 m (GGU 20714). The vein, which is vertical, 1 m wide with a general strike of 045° , can only be followed for 10 m due to vegetation. It is greyish-green, fine grained, locally with a black coating and is cut by millimetre wide quartz veinlets. Thin apophyses of the vein occur in cracks in the sandstone.

d) White albititic veins

Thin veins which consist only of albite are found all over the area. The veins are from one to a few millimetres thick. White albititic material also occurs in the earlier veins of the area. In the sandstone, veins of this type may contain a little quartz.

e) Carbonate veins

A few thin veins and irregular bodies consisting almost exclusively of calcite are found in the area. The veins are one millimetre to a few centimetres thick. These veins are rare, occurring mainly in the dykes and occasionally in the lavas. Small clusters of chalcedony and a little chlorite may occur in addition to the calcite. No relationship to the other vein types has been established in the field.

Veinlets of calcite have been seen in thin sections of the brown albititic, green and composite veins, but not in the two thin sections of quartz veins examined.

f) Quartz veins

Quartz veins are the most common veins in the area. They vary in thickness from about 1 mm to 20 cm, most commonly they are 2 to 5 cm thick. The veins may be traced for several hundred metres, but have mostly a length of only a few decimetres (fig. 4).

The quartz most often is massive; it is usually colourless, but there are white as well as red and green varieties. The coloured varieties often grow on or between larger colourless crystals. The red colouration is due to hematite and iron-manganese impregnations, the green due to numerous inclusions of minute ægirine needles. Often the inclusions are not distributed evenly and there are reddish-brown or black flakes of hematite and iron-manganese oxides between the quartz crystals. In some samples one end of a crystal is clear to white with a sharp contact against a yellowish-green part which in turn has a sharp contact with green quartz. The yellowish-green and green parts have few and many inclusions of small ægirine needles respectively.

The quartz crystals are normally subhedral with their *c* crystallographic direction at right angles to the wall rock. They project into cavities, which may be filled with small colourless quartz crystals of



Fig. 4. Quartz veins in lava at the coast 1 km SW of Mussartüt.

haphazard orientation. Such fillings are also found in the wall rock near the quartz veins.

Quartz veins also occur in, and intersect, green and albititic veins.

g) Composite veins

Usually the brown albititic and green ægirine veins occur in separate joints. Sometimes, however, they occur together in the same joints giving composite veins. These composite veins are in places attacked by later albitization, and are intersected by still later quartz and carbonate veinlets. Quartz may also occur as discontinuous stringers which are usually parallel to the strike of the veins though there may be local variations. The veins have inclusions of country rocks, especially of sandstone.

The brown albititic material forms bodies from a microscopic size up to several centimetres long. The bodies are irregular to more or less regular, and often elongated in shape. In the strongly albitized veins the green vein material may be strongly transformed and occurs as stringers or ellipsoidal bodies in which the ægirine may be transformed to aggregates of arfvedsonite. The different elongated bodies generally have their long direction parallel to the strike of the composite veins.

IV. ALTERATION OF THE COUNTRY ROCKS

The country rocks adjacent to the mineralized fracture zones, with the exception of those filled by quartz, are generally altered to a certain extent. The distance of alteration varies with the thickness of the veins. A few millimetres thick veins alter the country rock for a distance of one to a few centimetres, while metre-thick veins may have altered the country rock for several metres. Alteration of the lavas is seen as an intensification of the reddish-brown colour while the dykes are bleached adjacent to the veins, augite being transformed into ægirine. In the granite the feldspar is often recrystallized into albite and an actinolitic hornblende may be formed.

The alteration adjacent to the veins is most extreme in the red sandstone. The altered zone may be only a few millimetres in width or as much as five metres depending on the width of the vein. As a result of the alteration a green quartzitic rock is formed. Outside the alteration zone the green colouration may extend along joints and bedding planes in the sandstone. The sandstone is normally cross-bedded. This cross-bedding is preserved in the outer part of the alteration zone but close to the vein the rock becomes massive; only conglomerates preserve their structure right up to the vein contact.

The unaltered red sandstone is quartzitic with rounded quartz grains which show a secondary growth of quartz. The grains show a strong undulatory extinction. The colouration appears to be due to a pigmentation of the quartz grains. A few grains of hematite also occur in the sandstone. The conglomerates consist of larger aggregates of quartz grains in a matrix of quartz with a little microcline and chlorite. The aggregates may be coated with hematite.

In the green re-crystallized sandstone the quartz grains display a straight extinction and there are no signs of a secondary overgrowth of quartz. The new quartz may have many inclusions of small ægirine needles normally less than 0.01 mm long, and feldspar laths.

V. RADIOACTIVITY

The investigation of the radioactivity on the Ilimaussaq peninsula started as a geiger survey. More than 600 measurements were made over the area using different instruments. For comparative purposes all the readings are given in mR/h. Background readings are 0.01–0.03 mR/h.

The radioactivity of the larger mineralized zones and some of the smaller ones are indicated on the map (plate 3). No attempt has been made to separate the different vein types on this map. Since different vein types may occur in the same mineralized zone, the variability in geiger measurements is partly due to different types of vein, but even the same vein type may show a great variability over a few metres, particularly the brown albititic veins.

Besides the geiger measurements on the mineralized zones, readings were also taken on the country rocks, particular attention being given to the conglomeratic horizons in the sandstone. However, the readings on the country rocks have usually not been higher than the background readings, and never higher than 0.03 mR/h.

Maximum, minimum, and average readings are presented in table 1. The quartz, white albititic and carbonate veins did not give readings higher than the background readings.

The radioactivity of about 400 samples was measured in the laboratory, and 70 of these samples, showing the highest radioactivity, were analyzed for uranium and thorium.

Table 1. *Geiger readings on the different vein types in mR/h*

| | Maximum | Minimum | Average |
|-----------------------------|---------|---------|---------|
| Mineralized cracks..... | 0.20 | 0.02 | 0.05 |
| Brown albititic veins | 1.10 | 0.05 | 0.2 |
| Green veins | 0.60 | 0.03 | 0.2 |
| White albititic veins | * | * | * |
| Carbonate veins..... | * | * | * |
| Quartz veins..... | * | * | * |
| Composite veins..... | 0.60 | 0.05 | 0.1 |

* Background.

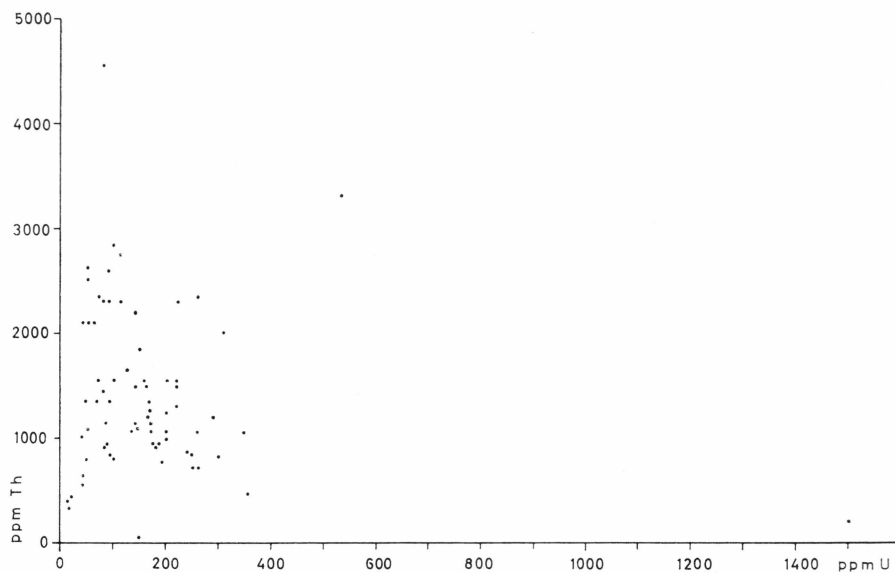


Fig. 5. Uranium and thorium content in all analyzed veins.

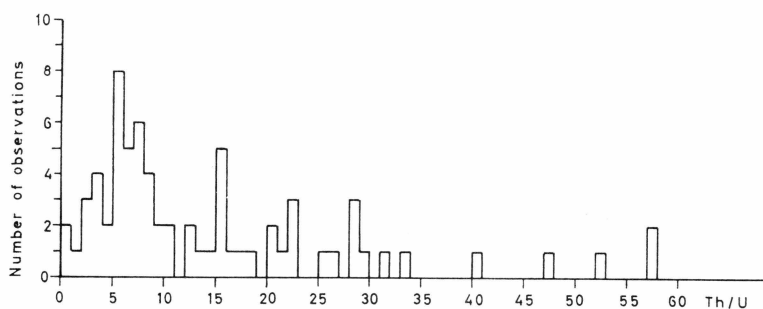


Fig. 6. Histogram of the number of observations against the ratio Th/U in 70 samples.

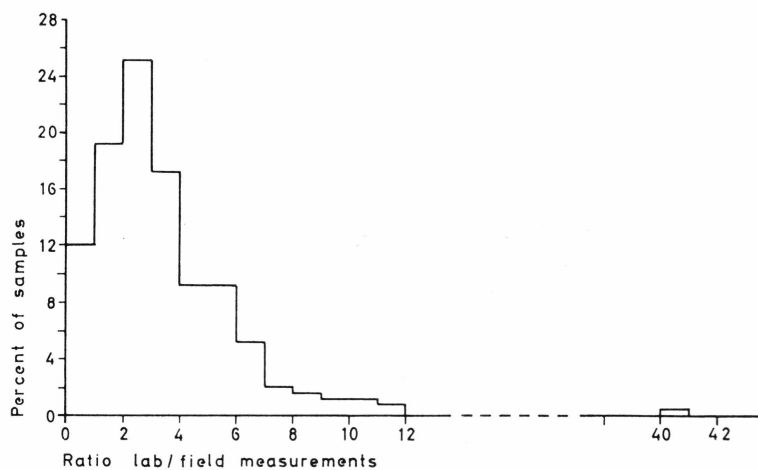


Fig. 7. Histogram of the ratio laboratory/field geiger readings.

Determinations of uranium and thorium have been made spectrophotometrically by E. SØRENSEN and T. LUNDGAARD of the Danish Atomic Energy Commission. The results are plotted in fig. 5. The thorium content ranges from 60 to 4500 ppm (mean $\bar{x} = 1405$, standard deviation $s = 793$ ppm). The uranium content ranges from 17 to 1500 ppm (mean $\bar{x} = 168$, standard deviation $s = 187$ ppm). The ratio thorium to uranium ranges from 0.1 to 57.2 (mean $\bar{x} = 14.6$, standard deviation $s = 13.2$ ppm) (see fig. 6).

No systematic variation is seen in the thorium and uranium contents, or in the thorium/uranium ratio according to vein type. Only two samples of the mineralization along joints and cracks have a higher uranium than thorium content.

In order to make a closer examination of the radioactive minerals an autoradiographic examination was made (see p. 26).

The radioactivity of samples measured in the laboratory was found to be considerably different from the radioactivity measured in the field. The ratio of laboratory/field readings varied from 0.6 to 41.0, with a mean \bar{x} of 5.4 and standard deviation $s = 3.1$ – 3.2 (fig. 7).

VI. PETROGRAPHY

a) Brown albititic veins

The mineral content of the brown albititic veins varies markedly from place to place both along and across the veins but no systematic variation or zoning is apparent. The veins consist dominantly of pigmented albite, together with hematite and quartz. Calcite, mica, apatite, chlorite, monazite, an eudialyte-like mineral and thorite may occur in accessory amounts.

Albite most often makes up more than 70 % of the vein rock with a maximum content of about 95 %. It is twinned on the albite law, either with a single twin plane or with polysynthetic twins. The grains are from a few hundredths of a millimetre to half a millimetre long often arranged more or less parallel to the strike of the veins. There are inclusions of small apatite needles and a brown pigmentation of iron-manganese oxide.

The hematite varies in amount from less than 1 % to approximately 10 % of the vein, occurring as disseminated grains as well as fillings in cracks in the feldspar and in the strongly undulatory quartz. The iron oxide has a high content of manganese. Radioactivity is connected to the iron-manganese oxide, especially to the border zone of the grains.

Quartz occurs both as separate grains and as veinlets. The individual grains, up to 2 millimetres across, have a strong undulatory extinction, and are probably derived from the sandstone. Cracks in these grains may be filled by hematite. Vein quartz cuts feldspar crystals, and may occur associated with calcite in cracks in the country rocks. The vein quartz may have inclusions of albite and hematite.

Calcite veinlets cut all the other minerals except the quartz of the veinlets, and calcite also occurs as separate grains constituting up to 5 % of the vein.

Chlorite is sometimes found in veins associated with hematite.

Both brown and white mica occur; the latter is a lithium-bearing variety.

Thorite occurs as a yellow, red or brown, finely disseminated mineral. It may be very weakly anisotropic, but most often it is isotropic. The mineral is often strongly pigmented by hematite in the border zone of

the vein. This pigmentation may extend over a whole grain making it opaque.

Monazite is found as separate grains up to 0.1 millimetre which may occur together in clusters. These clusters may be found in late quartz, but not in albite indicating a late formation of the monazite. The mineral is usually pigmented with iron oxides and crowded with small ægirine needles which may make it opaque. In places the grains are only very weakly pigmented.

b) Green veins

All the green veins contain albite with ægirine and/or acmite. Some have microcline and hematite with one or more of the accessory minerals: chlorite, apatite, mica, quartz, sphalerite, monazite, bastnäsite, neptunite, thorianite and thorite (see plate 1).

Ægirine/acmite makes up from approximately 20 % to more than 50 % of the veins. It occurs as needles or prisms generally 0.01 to 0.5 mm long, some up to 3 mm, arranged more or less parallel to the strike of the veins, occasionally arranged like felt. The ægirine grains may have a rim of acmite and acmite a rim of ægirine. In a few examples ægirine has a rim of arfvedsonite. Acmite is also found secondary after arfvedsonite. The ægirine is usually fresh but may be replaced by biotite and iron oxides.

Albite makes up from 30 to 70 % of the veins. It occurs as small euhedral laths 0.01 to more than 3 mm long twinned on the albite law and may be pigmented by iron oxides, particularly along cracks and against adjacent grains. The laths often have a parallel orientation. Inclusions of ægirine and small needles of apatite may occur.

Microcline occurs as separate grains up to 0.05 mm long and as inclusions in albite. It may be partly transformed to albite.

The opaque mineral, which was identified by X-ray powder methods as hematite, occurs both as an accessory constituent and as a major constituent forming up to 6.4 vol. % of the veins. It occurs as separate grains and as a coating on other minerals. It is normally a primary mineral but it occurs as a secondary constituent where it is associated with ægirine/acmite, which it may replace.

Lithium-mica forms flakes up to 2 mm across and may have inclusions of ægirine and albite. Biotite occurs as small (less than 0.1 mm) flakes in secondary acmite after arfvedsonite. It is often associated with hematite.

Pigmented grains of quartz with strong undulatory extinction occur interstitially between other minerals, and as veinlets which cut the other minerals. The strongly undulatory grains have a border zone with ordi-

nary extinction. It is suggested that this strongly undulatory quartz is derived from the sandstone.

Among the accessory minerals arfvedsonite is the most common. It has a bluish to yellow-green pleochroism with abnormal interference colours. It mostly occurs as a border to ægirine.

Bastnäsite occurs as individual, hexagonal grains up to 0.2 mm which are greyish. It may have a transparent border zone on a pigmented core. Most often however the whole grain is pigmented. The pigmentation is due to inclusions of small (less than 0.01 mm) ægirine needles. Bastnäsite may also have inclusions of albite, microcline and hematite.

Monazite occurs as individual grains up to 0.2 mm which are greyish. It may like bastnäsite be partly transparent but most often the grains are strongly pigmented due to inclusions of small ægirine needles. Monazite may also have inclusions of small laths of albite and microcline.

Thorite is yellow-green to red-brown due to pigmentation by hematitic material. The mineral is weakly anisotropic to isotropic and mostly occurs finely disseminated as grains up to 0.7 mm across.

From the textural arrangement of the minerals the following sequence of the major mineral formation has been deduced:

(earliest) ægirine/acmite — microcline — albite — hematite — bastnäsite (latest).

c) Composite veins

These veins are composed of patches of brown pigmented albititic material and lenses of ægirine and arfvedsonite enclosed in a greyish-white matrix of albite. In addition, quartz, neptunite, eudialyte, thorite and monazite may be found.

The albite matrix consists of small, clear to weakly pigmented laths with a more or less parallel alignment.

The brown inclusions consist of strongly pigmented albite laths. There is a distinct contact between the clear to weakly pigmented albite of the matrix and the strong pigmentation of the inclusions. Albite also occurs as veinlets composed of small, clear grains. The veinlets are up to 1 mm wide and cut the other minerals.

The lenses of ægirine, up to 4 mm long, consist of 0.2 mm long needles of ægirine. The lenses all have their long axes parallel. In a few samples stringers a few mm thick are built up of ægirine fibres. Ægirine is also found as separate grains, either as prisms about 0.1 mm long, or as poikilitic grains up to 0.7 mm long with inclusions of albite. The separate grains have a more or less parallel orientation. In a few examples the ægirine has rims of arfvedsonite.

Arfvedsonite is also found as lenses consisting of radiating grains.

These lenses are up to 4 mm long. The grains may have either border zones or cores of acmite.

Quartz occurs both as veinlets with inclusions of fine grained feldspar laths and ægirine, and as grains thought to be derived from the sandstone as they are heavily pigmented with hematite and have a strong undulatory extinction.

Eudialyte occurs as small strongly pigmented platy grains. The grains are usually partly altered to the isotropic mineral mesodialyte.

Thorite is found as yellow-red to red isotropic grains with a black border zone which may extend to cover the whole grain (see p. 26). Hematite is often associated with this mineral.

VII. CHEMICAL, SPECTROCHEMICAL AND X-RAY FLUORESCENCE ANALYSES

Chemical, spectrochemical and X-ray fluorescence analyses have been undertaken on the different vein types. The results are presented in table 2.

In the brown albititic and green veins the radioactivity is dominantly due to thorium while in the mineralized cracks it may be due to uranium (see p. 26).

The cracks with the highest uranium content are also those with the highest content of zirconium.

The phosphorus content is highest in those brown albititic veins which are most rich in monazite.

Other elements do not vary according to vein type nor is there a correlation between any of the elements uranium, thorium and the rare-earths suggesting that the radioactive minerals are randomly distributed and vary independently in the veins. This random distribution is in agreement with the petrographical examination which has shown an erratic distribution of the radioactive minerals both along and across the veins.

Table 2. *Analyses*

| Spec. No.: | Type of sample: | Chemical analyses | | | | | | | | |
|-------------|-----------------|-------------------|------|-------------------|------------------|------|------|------|--------------------------------|------------------|
| | | ppm | | weight % | | | | | | |
| | | Th | U | Na ₂ O | K ₂ O | MgO | CaO | FeO | Fe ₂ O ₃ | TiO ₂ |
| 20709 | G. V. | 1100 | 50 | 12.1 | 0.00 | 0.1 | 0.34 | — | 17.0 | 0.48 |
| 20713 | — | 1043 | 125 | 5.8 | 2.9 | — | — | — | — | — |
| 20714 | — | 1168 | 130 | 6.21 | 0.00 | 0.22 | 0.48 | — | 7.86 | 0.17 |
| LB 549 | — | 2200 | 137 | — | — | 0.2 | 0.1 | — | 7.1 | 0.16 |
| 20753 | — | 1015 | 127 | 7.60* | 0.00* | 0.28 | 2.38 | — | 8.78 | 0.29 |
| 20721 | B. A. V. | 553 | 72 | 5.98 | 0.00 | 0.37 | 0.70 | — | 12.04 | 0.38 |
| 20731 | — | 1215 | 87 | 6.94 | 0.18 | 0.94 | 0.00 | 2.01 | 7.60 | 0.24 |
| LB 189 | — | 3320 | 531 | — | — | — | 1.8 | 0.00 | 7.5 | 0.26 |
| LB 545 | — | 1065 | 48 | — | — | — | — | — | — | — |
| LB 143 | M. C. | 200 | 1500 | — | — | — | 0.92 | — | 11.5 | 2.94 |

G. V. green vein; B. A. V. brown albititic vein; M. C. mineralized crack; tr. trace. Thorium and uranium GRUMLØSE and the author, spectrochemical analyses by H. BOLLINGBERG and the author. Chemical

VIII. MINERALOGY

Non-radioactive minerals

Ægirine as used in this paper is the soda pyroxene which in thin section is green to colourless, while acmite in thin section is brown to colourless (*cf.* USSING, 1894 p. 198, SABINE, 1950, SCHÜLLER, 1958 and SØRENSEN, 1962 p. 215).

Ægirine and acmite have in this investigation been found as 1) thin needles in albite, microcline, quartz, bastnäsite and monazite, 2) poikilitic grains with inclusions of albite and microcline, and 3) lenses and stringers consisting of haphazardly orientated needles of ægirine. The ægirine grains, like those in Ilímaussaq (USSING, 1894 p. 182 and SØRENSEN, 1962 p. 216) often have a green core and a bleached border zone with bleaching also along fractures in the grains. Ægirine may be partly altered to acmite and arfvedsonite.

The ægirine has

$$z \wedge c = 85-90^{\circ}, n_{\alpha} = 1.76 \quad n_{\gamma} = 1.82, n_{\gamma} - n_{\alpha} = 0.06.$$

of the veins

| | | | | | X-ray fluorescence analyses | | | | | Spectrochemical analyses | | |
|--------------------------------|-------------------------------|-----------------|-------------------------------|--|-----------------------------|------|--------------------------------|-------------------------------|--------------------------------|--------------------------|------|--------|
| | | | | | weight % | | | | | weight % | | |
| Al ₂ O ₃ | P ₂ O ₅ | CO ₂ | H ₂ O ⁺ | | ZrO ₂ | ZnO | La ₂ O ₃ | Y ₂ O ₃ | Ce ₂ O ₃ | Zr | Mn | V |
| — | — | — | — | | tr. | 0.03 | tr. | tr. | 0.2 | 0.00 x | 0.16 | 0.00 x |
| — | — | — | — | | tr. | 0.04 | tr. | tr. | 0.3 | 0.00 x | — | — |
| 6.18 | 0.26 | 0.00 | 0.24 | | — | — | — | 0.1 | — | — | 0.39 | — |
| — | — | — | — | | 0.03 | tr. | — | 0.05 | 1.4 | — | 0.1 | — |
| 10.61 | 0.35 | — | 0.14 | | — | — | — | — | — | — | 0.68 | — |
| 10.55 | 0.90 | 0.00 | 0.88 | | 0.02 | 0.1 | 0.1 | 0.1 | 0.4 | — | 0.31 | — |
| 11.80 | 1.05 | 0.00 | 0.88 | | — | 0.1 | 0.2 | 0.02 | 0.6 | — | 3.26 | — |
| — | — | — | — | | — | 0.1 | 0.2 | 0.03 | 0.8 | — | 0.2 | 0.00 x |
| — | — | — | — | | — | 0.1 | 0.2 | tr. | 0.3 | — | 0.7 | — |
| — | — | — | — | | — | 0.1 | 0.1 | 0.03 | 0.2 | 0. x | — | 0. x |

determined by T. LUNDGAARD and E. SØRENSEN, A.E.C., Risø. X-ray fluorescence analyses by M. analyses by B. I. BØRGEN (except uranium and thorium and * by ME MOURITZEN).

A spectrochemical analysis of ægirine (GGU 47124) gave the following results in weight percent:* Ti 0.0X, Zr 0.0X, Mn 0.0X, and V 0.00X. Ba, Sr, Yb and La were looked for but not detected. This differs from Ilímaussaq where V has not been detected in ægirine (O. LARSEN, personal communication).

According to SCHÜLLER (1958) the green colour of ægirine is caused by the partial substitution of the Fe^{3+} of acmite by small amounts of Fe^{2+} . The acmite thus represents a higher stage of oxidation than the ægirine.

Albite most often occurs as approximately 0.01 to 0.1 mm long laths, but laths a few millimetres long are occasionally found. The grains are twinned on the albite law, either with a single twin plane or with polysynthetic twins.

Due to the small size of the feldspar laths the composition was most often determined by measurement of the maximum extinction angle (Michel-Lévy method). These determinations, which were confirmed by a few determinations on the universal stage, have given compositions from $\text{Ab}_{100}\text{An}_0$ to $\text{Ab}_{90}\text{An}_{10}$; $2V_\alpha$ is $70\text{--}82^\circ$. This is in good agreement with determinations undertaken by SØRENSEN (1962 p. 216) on albite from Ilímaussaq where he found $2V_\alpha = 74\text{--}88^\circ$. Guinier powder diagrams of albite (GGU 20713) have given $a_0 = 8.144$, $b_0 = 12.787$ and $c_0 = 7.160$. The same constants are found for low temperature albite from Amelia, Virginia (SMITH, 1956) which has the composition $\text{Ab}_{98.2}\text{Or}_{1.8}$.

Arfvedsonite is only found in the green and composite veins. The mineral has pleochroism from bluish green to yellow-green with abnormal interference colours (*cf.* SAHAMA, 1956). It may be surrounded by an aggregate of small acmite needles, which, it is suggested, are an alteration product of the arfvedsonite. The secondary acmite is often associated with small scales of brown mica. Arfvedsonite is also found as an alteration product of acmite and in rare cases replacing ægirine.

Apatite, as in the Ilímaussaq intrusion (SØRENSEN, 1962 p. 218), is a rare mineral. It is only found as small grains in albite in the brown albititic and green veins.

Biotite is only found as small flakes in secondary acmite after arfvedsonite and associated with hematite. The grains are only a few hundredths of a millimetre long. The mineral is optically negative with a very small axial angle; α brown and $\beta = \gamma$ dark brown. The grains like those in Ilímaussaq are elongated along the c axis. It is suggested that the mineral formed at the expense of arfvedsonite deriving small amounts of magnesium from the arfvedsonite (*cf.* SØRENSEN, 1962 p. 219).

* The figures here are to the nearest factor of 10.

Calcite, identified by its refractive indices, is found in thin veinlets which cut all the other minerals, with the exception of the late quartz, and also occurs interstitially between the other minerals. This shows a very late formation for the calcite.

Chlorite is found in albititic veins, green veins and in the mineralized cracks. Under the microscope it is pleochroic from yellowish green to green. $n_\beta = 1.58$; birefringence ≈ 0.01 . The mineral is an alteration product of the pyriboles.

Eudialyte is found in a few thin sections as small plates often with a strong pigmentation. The mineral is uniaxial positive, length fast with high refractive indices and low birefringence ≈ 0.01 . The platy grains have the c -axis perpendicular to the long direction of the grains. The grains often have irregular isotropic patches of mesodialyte (*cf.* USSING, 1894 p. 145, and SØRENSEN, 1962 p. 221).

Fluorite is found in the mineralized cracks. It occurs as small purplish crystals mixed with coarsely crystalline quartz. It is associated with albite, chlorite, hematite, quartz and apatite.

Hematite is a characteristic mineral of the albititic veins and the mineralized cracks, but is found in all the vein types. It is primary as well as secondary. Hematite occurs as a pigmentary material in the other minerals, especially in the feldspar and in the radioactive minerals. The latter minerals may be quite opaque due to hematite impregnation. Hematite also occurs as thin veinlets which cut the other minerals. Secondary hematite is formed by alteration of minerals such as ægirine, acmite and arfvedsonite.

Iron-manganese oxides occur as earthy to metallic bluish to black coatings on other minerals. X-ray powder diagrams of the coatings only indicate hematite while X-ray fluorescence analyses have shown a high content of manganese, thorium and uranium.

Lithium-mica is found as grains up to 2 mm across in the green veins and may be developed in a star-like pattern and have inclusions of ægirine and feldspar. It has $n_\gamma = 1.555$ and $2V \approx 45^\circ$, and according to the X-ray diagrams the mineral is lepidolite. (A closer examination of the micas in Ilímaussaq is being undertaken by the author).

Microcline is found in the green veins. The mineral is found as separate grains up to 0.02 mm long as well as occurring as inclusions in albite, to which it may be partly transformed. It has a chess-board type of penetration twinning and differs from microcline of granites etc. in lacking the cross-hatched twinning (*cf.* discussion by SØRENSEN, 1962 p. 224). $2V_\alpha$ is $75-84^\circ$: SØRENSEN (p. 225) found that $2V_\alpha$ of microcline

from Ilmaussaq is 76–88°, with most determinations in the interval 76–82°.

It is thought that the chess-board microcline formed directly with a maximum triclinic symmetry at a low temperature (approximately 300° C) (*cf.* SØRENSEN *loc. cit.*).

Small grains of neptunite are found in the green veins where it is associated with albite, microcline, ægirine, hematite and thorite. The mineral is particularly common in connection with ægirine partly altered to hematite. Neptunite is strongly pleochroic with α orange-yellow, β orange and γ red. The refractive indices are higher than 1.68.

Pyrite has been observed in the mineralized cracks. It has rusty border zones and is associated with chlorite and other minerals.

Quartz is found interstitially and as thin veinlets which cut the other minerals. Quartz is also found as grains with strong undulatory extinction in the central parts and with recrystallized borders. Zones of dust often indicate the original outlines of the grains. This quartz is probably derived from the sandstone.

The late quartz is generally fine-grained, transparent to milky white, but it may be green or reddish. The green colour is due to inclusions of small (less than 0.01 mm long) needles of ægirine. The red colour is due to hematite impregnation. At places transparent veinlet quartz grades into green or red varieties.

Sphalerite has been identified in reflected light. It is only found in a few samples from the green veins, where it is associated with albite, quartz, ægirine, acmite, and apatite.

Radioactive minerals and autoradiography

All the veins except the quartz, white albititic and carbonate veins are radioactive (table 1). The brown albititic and green veins are thorium mineralized, while the mineralized small cracks are uranium mineralized.

An autoradiographic examination was undertaken in order to locate the radioactive minerals in thin sections. The procedure used is that described by BUCHWALD and SØRENSEN (1961). The results are given in table 3.

The radioactivity is most often connected with pigmentary material, which in some cases has been identified as hematite by means of X-ray powder diagrams, and to small isotropic to weakly anisotropic grains which are more or less pigmented by iron oxides. Most often the pigmentation is most intensive in the border zone of the host mineral which may contain so much hematitic dust that it is opaque. X-ray powder diagrams

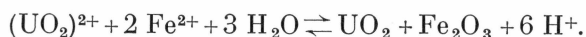
Table 3. *Results of an autoradiographic examination*

| | α /cm ² /hour | | | (maximum values) |
|------------------------------------|---------------------------------|--------------------|-----------------------|------------------|
| | Conglomerates, Sandstones | Mineralized Cracks | Brown albititic veins | Green veins |
| Unidentified pigmentary material.. | 1 000 | 2 000 | 20 000 | 10 000 |
| Thorianite..... | | | | > 50 000 |
| Thorite..... | | | > 50 000 | > 50 000 |
| Hematite*..... | | | 1 000 | 5 000 |
| Monazite..... | | | 1 000 | |
| Bastnäsité..... | | | | 5 000 |
| Pyrite..... | | 1 000 | | |
| Rusty border zone of pyrite*..... | | 20 000 | | |
| Apatite..... | | 50 | 50 | |
| Zircon..... | 1 000 | | | |

* Due to adsorbed uranium.

of the radioactive material are most often without reflections, but may show lines of hematite, more seldom of hematite and additional very diffuse lines which it has been impossible to identify. In a very few instances the diagrams of the radioactive material in the green veins gave very diffuse lines of thorianite which it is suggested is an alteration product of thorite or thorogummite.

In the mineralized small cracks the radioactivity is most often associated with pyrite and especially with its rusty border zones. As seen in table 2 these veins are uranium mineralized and the uranium is probably adsorbed on the oxidized pyrite (hematite) according to the reaction:



This may take place when the solution comes into contact with pyrite because the energy of transformation UO_2 to $(\text{UO}_2)^{2+}$ is lower than the energy corresponding to the oxidation of Fe^{2+} to Fe^{3+} . The equation is displaced entirely to the right at pH = 4, T = 25° C. (McKELVEY, 1955).

In the brown albititic and in the green veins radioactivity is often connected to small green-yellow to red-brown grains which may be strongly pigmented by iron oxides. The pigmentation may be so intense that the grains are quite opaque. The mineral is isotropic and occurs as a finely disseminated aggregate in grains up to 0.7 mm. The refractive index is ≈ 1.71 . X-ray fluorescence analyses combined with spectrochemical analyses have given mainly thorium and silicon, together with 2 %

U, 3 % Fe, 1 % Ca, 0.3 % Ti, 1 % Ce, 0.01 % Cu, 1 % Y, 0.1 % La, 1 % Zr, 0.7 % Mn and traces of Pb. Ba, Sr, Sc, Cr, V, Ta, Co, and Ni have been looked for but not detected.

The mineral did not give any lines on X-ray powder diagrams before heating. After heating to 800° C for 1 hour in air very weak diffuse lines of cubic ThO₂ were obtained and after heating to 1100° C for 1 hour thick diffuse lines of the same "mineral". The lines are diffuse due to small particle size.

BERMAN (1955) has heated completely metamict thorites at different temperatures and pressures. Heating at 800° C for one minute or more gave cubic ThO₂, heating at 1100° C for longer periods of time produced monoclinic ThSiO₄ or tetragonal ThSiO₄ and cubic ThO₂. The behaviour of the different samples varied considerably, presumably partly due to differences in composition and partly due to the degree of metamictization of the original sample.

The chemical composition, refractive index and heating results indicate a metamict thorite, which according to FRONDEL (1958) has a refractive index from 1.66 to 1.87.

In fig. 8 and 9 the results of a micro-DTA analysis and a thermoluminescence analysis are given.

Rare-earth minerals

a) Bastnäsite

Bastnäsite from Greenland was first recorded by DONNAY and DONNAY (1953) in material from Narssârssuk. The description given here is the first detailed account of the mineral from Greenland; the occurrence has already been mentioned by BUCHWALD *et al.* (1960). Bastnäsite has also been identified in pegmatites in the Malenefjeld granite of the Nunarssuit complex (HARRY and PULVERTAFT, 1963 p. 54), but no data were given from this occurrence.

Bastnäsite only occurs in the green veins where it is associated with microcline, albite, ægirine, hematite, monazite, neptunite and veinlets of quartz. It occurs in up to 1 mm, euhedral to anhedral grains, which may have hexagonal outlines. The mineral is colourless to very weakly pale yellow, with a very weak pleochroism from light yellow to yellow. The mineral may have a colourless border zone and a pigmented core due to numerous inclusions of ægirine needles less than 0.01 mm long. The pigmentation may extend all over the grains making them almost opaque. In addition to ægirine, bastnäsite has inclusions of small albite and microcline laths. Bastnäsite is uniaxial positive with $n_{\omega} = 1.722$ and $n_{\epsilon} = 1.823$;

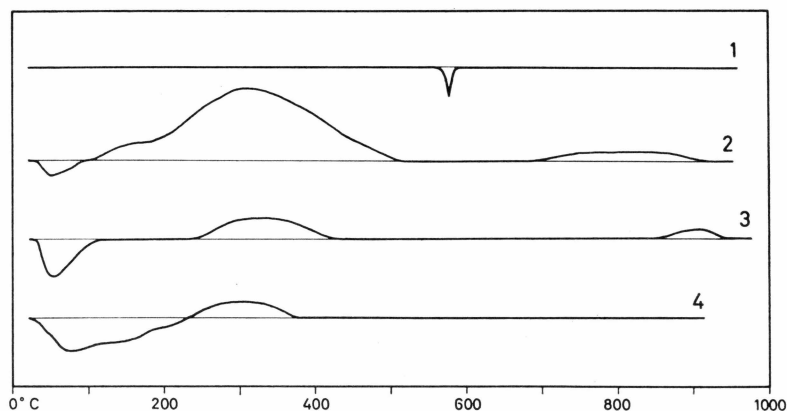


Fig. 8. Differential thermal analyses.

Curve 1: Quartz for comparison.

Curve 2: Thorite.

Curve 3: Thorite from Langesund, Norway.

Curve 4: Bastnäsite.

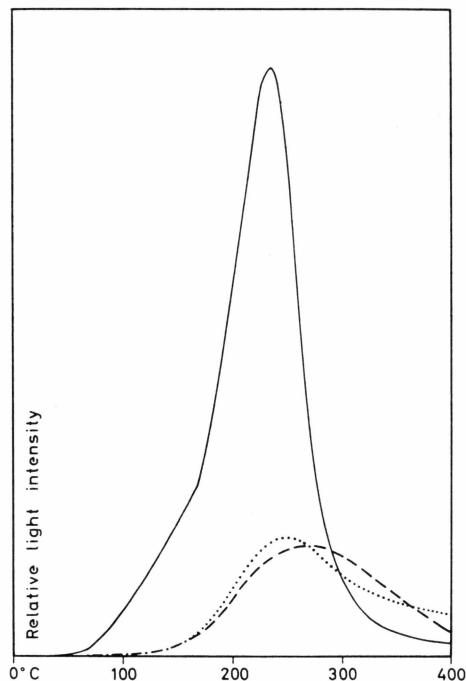


Fig.9. Glow curves.

----- Bastnäsite, natural.

..... Thorite, natural.

———— Bastnäsite, after heating to approximately 400°C and exposure to 10^6 rad Co^{60} γ radiation.

The diagrams are redrawn for the same amount of material and the same amplification.

Table 4. *Refractive indices of bastnäsite from different localities*

| | | n_{ω} | n_{ε} | $n_{\varepsilon} - n_{\omega}$ |
|---|------------------------------|--------------|-------------------|--------------------------------|
| Sweden, Bastnäs | (GEIJER, 1921)* | 1.7225 | 1.8242 | 0.1017 |
| | GLASS & SMALLEY, 1945) | 1.7220 | 1.8235 | 0.1015 |
| Ruanda Urundi | (GLASS & SMALLEY, 1945) | 1.722 | 1.823 | 0.101 |
| USA, Pikes Peak, Colerado | (LARSEN, 1921) | 1.717 | 1.818 | 0.101 |
| USA, Jamestown, Colerado | (GODDARD & GLASS, 1940) | 1.716 | 1.817 | 0.101 |
| USA, Mountain Pass, California | (OLSON <i>et al.</i> , 1954) | 1.722 | 1.823 | 0.101 |
| USA, Callinas Mt., New Mexico | (GLASS & SMALLEY, 1945) | 1.718 | 1.819 | 0.101 |
| Madagascar | (LACROIX, 1922) | 1.714 | | |
| | (GLASS & SMALLEY, 1945) | 1.717 | 1.818 | 0.101 |
| Greenland, Narssârssuk ... | (DONNAY & DONNAY, 1953) | 1.718 | 1.818 | 0.100 |
| Greenland, Nunasarnaq ... | (Present report) | 1.722 | 1.823 | 0.101 |

* Indices were determined on prisms cut parallel to the prismatic cleavage.

$n_{\varepsilon} - n_{\omega} = 0.101$. The refractive indices are in good agreement with the data from other localities given in table 4.

An X-ray investigation using a Guinier-Hägg camera has been undertaken using quartz as an internal standard. The camera was calibrated by means of the observed quartz lines and lattice constants for quartz as given by SWANSON and FUYAT (1954). In the calculations of lattice constants the weighted mean of α_1 and α_2 wavelengths for copper radiation of 1.5418 Å was used.

It was not possible to separate the associated monazite and inclusions of ægirine, albite and microcline from bastnäsite so that these associated minerals have also been identified in the powder diagram, thus confirming their presence.

The governing principle for classifying a specific line with one mineral was that all strong lines of the mineral should be present. In table 5 the bastnäsite from Nunasarnaq is compared with bastnäsite from the ASTM powder diffraction file no. 11-340. The following should be noted: 1) all but three of the bastnäsite lines given in the ASTM powder diffraction file are present; 2) all but three of the albite lines with intensities higher than or equal to 9 are present; 3) only the two strongest lines of ægirine are present; 4) that all except the weakest lines of monazite are present, and 5) only two lines of microcline are present.

Only lines of bastnäsite which do not coincide with lines of other minerals have been used for the final refinement. This refinement has been made by the least square method with a program REFBASE II made by E. LEONARSEN on a GIER computer.

The constants calculated from the diagram are given below, together with those from the ASTM index for comparison. It is seen that the agreement is very good.

| | These veins (GGU 20714) | ASTM file no. 11-340 |
|-----------|--|----------------------|
| a_0 | $7.120 \pm 7 \times 10^{-3} \text{ \AA}$ | 7.129 \AA |
| c_0 | $9.77 \pm 2 \times 10^{-2} \text{ \AA}$ | 9.774 \AA |
| c_0/a_0 | 1.372 | 1.371 |
| V_0 | 428.96 \AA^3 | |

Since there was insufficient material for a chemical analysis a semi-quantitative spectrochemical analysis was made, with the following results:

| | |
|----|---------------|
| Ce | 25-30 % |
| Y | ≈ 1 % |
| La | ≥ 1 % |

Ba, Sr, Yb, Na, Ti, Ca, and Zr were looked for, but not detected.

An absorption measurement undertaken with a Beckmann Spectrophotometer directly on a thin section perpendicular to the c axis of the mineral has given $\text{Pr} \ll \text{Nd}$.

The spectrochemical analysis is in good agreement with an analysis of bastnäsité from Westerly, Rhode Island, USA (SMITH and CISNEY, 1956) which gave

| | |
|-------------------------|--------------|
| Ce | > 10 % |
| Pr, Gd, Sm, Y: | 0.1-0.5 % |
| La, Nd: | 1-5 % |
| Dy, Er, Eu, Lu, Tb, Sc: | 0.01-0.05 % |
| Ho, Yb: | 0.005-0.01 % |

A micro-differential thermal analysis of bastnäsité is given in fig. 8 (see p. 36 and a thermoluminescence diagram in fig. 8 (see p. 37).

GLASS and SMALLEY (1945) considered bastnäsité to occur most frequently in contact metamorphic zones. PERHAC and HEINRICH (1964) reviewing 27 occurrences from the literature have found that bastnäsité is most commonly an accessory mineral in alkali granites, syenites, and pegmatites where it is a late mineral, but it also occurs in hydrothermal, contact-metasomatized and carbonate deposits. Bastnäsité is predominantly associated with other rare-earth minerals. Bastnäsité is also found in epithermal hydrothermal veins *e.g.* in Gallinas Mountains, New Mexico (PERHAC and HEINRICH 1964), where it is associated with quartz, barite, sulphide minerals, fluorite etc. Bastnäsité may in addition be an alteration product of parisite (SEMENTOV *et al.*, 1961), allanite (SILVER and GRUENFELDER, 1957 and SVERDRUP *et al.*, 1959) and tysonite (HILLEBRAND, 1899).

From these occurrences it can be concluded that bastnäsite is formed in a wide range of P/T conditions.

b) Monazite

Monazite is found in green veins and in the brown albititic veins where it is associated with albite, hematite, apatite and late quartz. It is found as separate grains up to 0.1 mm across and as small clusters of

Table 5. *Guinier powder diagram of bastnäsite*

| Sin ² θ obs | Sin ² θ calc | Bastnäsite these veins | | | Intern. standard quartz | Bastnäsite ASTM File no 11-340 | | | Impurities† |
|----------------------------------|-----------------------------------|---------------------------|------|----|-------------------------------|-----------------------------------|-------|-----|-------------|
| | | hkl | d | I | | hkl | d | I | |
| 0.01466 | 0.02491 | 002 | 6.37 | 1 | * | 002 | 4.88 | 40 | a |
| 0.02174 | | | 5.23 | 3 | | | | | mo |
| 0.02466 | | | 4.91 | 1 | | | | | |
| 0.02554 | | | 4.82 | 2 | | | | | mo |
| 0.02692 | | | 4.70 | 5 | | | | | mo |
| 0.03031 | | | 4.43 | 1 | | | | | ? |
| 0.03277 | 0.04689 | 110 | 4.26 | 15 | * | 110 | 3.564 | 70 | |
| 0.03375 | | | 4.20 | 6 | | | | | mo, m |
| 0.03513 | | | 4.11 | 3 | | | | | mo |
| 0.03662 | | | 4.03 | 1 | | | | | a |
| 0.04160 | | | 3.78 | 1 | | | | | a |
| 0.04715 | | | 3.55 | 4 | | | | | |
| 0.04797 | | | 3.52 | 5 | | | | | a, mo |
| 0.05316 | | | 3.34 | 20 | | | | | |
| 0.05412 | | | 3.31 | 8 | | | | | mo |
| 0.05751 | | | 3.22 | 2 | | | | | m |
| 0.05815 | | | 3.20 | 2 | | | | | a |
| 0.05982 | | | 3.15 | 2 | | | | | ? |
| 0.06159 | 0.06252 | 200 | 3.11 | 12 | * | 112 | 2.79 | 100 | mo |
| 0.06288 | | | 3.07 | 1 | | | | | |
| 0.06602 | | | 3.00 | 2 | | | | | æ, mo |
| 0.06682 | | | 2.98 | 4 | | | | | æ + |
| 0.06756 | | | 2.97 | 1 | | | | | a |
| 0.07174 | 0.07179 | 112 | 2.88 | 12 | | | | | mo |
| 0.08726 | 0.08742 | 202 | 2.61 | 3 | * | 202 | 2.610 | 1 | mo |
| 0.09077 | 0.09962 | 004 | 2.56 | 1 | | 004 | 2.445 | 9 | a |
| 0.09185 | | | 2.54 | 1 | | | | | æ |
| 0.09307 | | | 2.53 | 3 | | | | | mo |
| 0.09854 | | | 2.46 | 12 | | | | | mo |
| 0.10233 | | | 2.41 | 1 | | | | | mo |

(continued on opposite page)

Table 5 (cont.)

| Sin²θ obs | Sin²θ calc | Bastnäsite these veins | | | Intern. standard quartz | Bastnäsite ASTM File no. 11-340 | | | Impurities† |
|--------------|---------------|---------------------------|-------|----|-------------------------------|------------------------------------|-------|----|-------------|
| | | hkl | d | I | | hkl | d | I | |
| 0.10776 | | | 2.35 | 1 | | | | | mo |
| 0.11432 | 0.11525 | 104 | 2.28 | 12 | * | 104 | 2.273 | 3 | |
| 0.11888 | 0.11855 | 203 | 2.24 | 8 | | 230 | 2.238 | 3 | |
| 0.12299 | | | 2.20 | 4 | | | | | mo |
| 0.12829 | | | 2.15 | 4 | | | | | mo |
| 0.13133 | | | 2.13 | 10 | * | | | | mo |
| 0.14039 | 0.14066 | 300 | 2.06 | 1 | | 300 | 2.057 | 40 | |
| 0.14657 | 0.14657 | 114 | 2.01 | 1 | | 114 | 2.016 | 40 | |
| 0.15158 | | | 1.980 | 8 | * | | | | |
| 0.15645 | | | 1.949 | 1 | | | | | mo |
| 0.16346 | | | 1.907 | 2 | | | | | mo |
| 0.16797 | 0.16557 | 302 | 1.881 | 4 | | 302 | 1.898 | 40 | mo |
| 0.17994 | | | 1.817 | 15 | * | | | | |
| 0.18274 | | | 1.803 | 2 | | | | | mo |
| 0.18998 | 0.18755 | 220 | 1.769 | 2 | | 220 | 1.783 | 9 | mo |
| 0.19505 | | | 1.746 | 3 | | | | | mo |
| 0.20596 | | | 1.699 | 1 | | | | | mo |
| 0.21272 | 0.21245 | 222 | 1.671 | 10 | * | 222 | 1.674 | 21 | |
| 0.21610 | | | 1.658 | 6 | * | | | | |
| 0.22264 | 0.22415 | 006 | 1.634 | 1 | | 006 | 1.629 | 1 | |
| 0.22992 | | | 1.608 | 1 | | | | | |
| | 0.24028 | 304 | | | | 304 | 1.573 | 15 | |
| 0.25029 | | | 1.541 | 14 | * | | | | mo |
| | 0.27145 | 116 | | | | 116 | 1.481 | 9 | |
| 0.28145 | | | 1.453 | 4 | | | | | |
| | 0.28717 | 224 | | | | 224 | 1.439 | 11 | |
| 0.31110 | | | 1.382 | 12 | * | | | | |
| 0.31413 | | | 1.375 | 12 | * | | | | |
| 0.31550 | | | 1.372 | 12 | * | | | | mo |

† a = albite, m = microcline, æ = ægirine mo = monazite, + = 201 and 22̄1 splitting up in ægirine.

very small angular grains. These clusters often occur in the late quartz. The monazite may be clear, but most often it is pigmented with hematitic dust especially in the border zone. This pigmentation may occur throughout the whole grain making it opaque. The mineral is radioactive with up to 1000 α/cm²/hour (see p. 27).

The results of an X-ray investigation using a Guinier-Hägg camera is given in table 6 (the procedure used is described on p. 30).

The mineral is compared with monazite from the ASTM file no. 11-556 and with monazite from the Kvanefjeld area, Ilimaussaq. The constants calculated from the diagram are given on p. 36 together with those from the ASTM index for comparison. Agreement between the different material is good.

Table 6. *Guinier powder diagram of monazite*

| Sin ² θ obs | Sin ² θ calc | Monazite these veins | | | Intern stand. quartz | Monazite ASTM File no. 11-556 | | | Albite ASTM File no. 9-466 | Monazite Kvanefjeld | |
|----------------------------------|-----------------------------------|-------------------------|------|----|----------------------------|----------------------------------|------|-----|-------------------------------------|------------------------|----|
| | | hkl | d | I | | hkl | d | I | | d | I |
| 0.02184 | 0.02204 | 10 $\bar{1}$ | 5.22 | 4 | * | $\bar{1}$ 01 | 5.20 | 13 | | 5.25 | 1 |
| 0.02559 | 0.02570 | 110 | 4.82 | 2 | | 110 | 4.82 | 7 | | 4.86 | 1 |
| 0.02699 | 0.02704 | 01 $\bar{1}$ | 4.69 | 6 | | 011 | 4.66 | 18 | | 4.71 | 2 |
| 0.03278 | | | 4.26 | 15 | | | | | | 4.26 | 8 |
| 0.03387 | 0.03409 | 111 | 4.19 | 8 | | $\bar{1}$ 11 | | | | | |
| 0.03516 | 0.03526 | 101 | 4.11 | 4 | | 101 | 4.08 | 9 | | 4.13 | 1 |
| 0.03658 | | | 4.03 | 8 | | | | | × | | |
| 0.03994 | | | 3.86 | 1 | | | | | × | | |
| 0.04162 | | | 3.78 | 2 | | | | | × | | |
| 0.04371 | | | 3.69 | 1 | | | | | × | | |
| 0.04429 | | | 3.66 | 2 | | | | | × | | |
| 0.04728 | 0.04730 | 111 | 3.55 | 6 | * | | | | | 3.56 | 2 |
| 0.04813 | 0.04817 | 020 | 3.51 | 6 | | 111 | 3.51 | 25 | × | 3.53 | 2 |
| | | | | | | | | | | 3.44 | 2 |
| | | | | | | | | | | 3.43 | 4 |
| | | | | | | | | | | 3.35 | 18 |
| 0.05309 | | | 3.35 | 20 | | | | | | | |
| 0.05422 | 0.05463 | 200 | 3.31 | 10 | | 200 | 3.30 | 50 | | | |
| 0.05752 | | | 3.21 | 8 | | | | | | | |
| 0.05825 | | | 3.19 | 10 | | | | | × | | |
| 0.05853 | | | 3.19 | 2 | | | | | | | |
| 0.05913 | | | 3.17 | 1 | * | | | | | | |
| 0.05996 | 0.05998 | 002 | 3.15 | 6 | | | | | × | | |
| 0.06169 | 0.06182 | 120 | 3.10 | 15 | | 120 | 3.09 | 100 | | 3.12 | 6 |
| 0.06302 | 0.06316 | 021 | 3.07 | 1 | | | | | | | |
| 0.06640 | 0.06667 | 210 | 2.99 | 3 | | 210 | 2.99 | 18 | | | |
| 0.06767 | | | 2.96 | 2 | | | | | × | | |
| 0.06808 | | | 2.96 | 2 | | | | | | | |
| 0.06925 | | | 2.93 | 1 | | | | | × | 2.93 | 2 |
| 0.07206 | 0.07202 | 012 | 2.87 | 18 | | 012, $\bar{1}$ 12 | 2.87 | 70 | | 2.88 | 6 |
| 0.08147 | | | 2.70 | 1 | * | | | | | | |
| 0.08573 | 0.08818 | 20 $\bar{2}$ | 2.63 | 5 | | $\bar{2}$ 02 | 2.61 | 18 | | 2.62 | 1 |
| 0.09071 | | | 2.56 | 1 | | | | | | | |
| 0.09847 | | | 2.46 | 10 | | | | | | 2.46 | 4 |
| 0.09970 | 0.10022 | 21 $\bar{2}$ | 2.44 | 2 | | 112, $\bar{2}$ 12 | 2.44 | 18 | | | |
| 0.10252 | 0.10280 | 220 | 2.41 | 1 | | 220 | 2.40 | 5 | | | |
| 0.10835 | 0.10814 | 022 | 2.34 | 1 | | $\bar{1}$ 22, 022 | 2.34 | 5 | | | |

(continued on opposite page)

Table 6. (cont.)

| Sin ² θ obs | Sin ² θ calc | Monazite these veins | | | Intern stand. quartz | Monazite ASTM File no. 11-556 | | | Albite ASTM File no. 9-466 | Monazite Kvanefjeld | |
|---------------------------|----------------------------|-------------------------|-------|----|----------------------------|----------------------------------|------------|----|-------------------------------------|------------------------|---|
| | | hkl | d | I | | hkl | d | I | | d | I |
| 0.11062 | | | 2.32 | 1 | | | | | | | |
| 0.11422 | | | 2.28 | 10 | * | | | | | 2.28 | 4 |
| 0.11891 | 0.11809 | 30 $\bar{1}$ | 2.24 | 6 | * | 301 | 2.25 | 3 | | 2.24 | 2 |
| 0.12345 | 0.12337 | 031 | 2.19 | 6 | | 031 | 2.19 | 18 | | 2.20 | 1 |
| 0.12884 | 0.12878 | 10 $\bar{3}$ | 2.15 | 6 | | 103 | 2.15 | 25 | | 2.16 | 1 |
| 0.13143 | 0.13101 | 221 | 2.13 | 8 | * | 221, $\bar{1}$ 31 | 2.13 | 25 | | 2.13 | 3 |
| 0.15170 | | | 1.979 | 4 | * | 013, 131 | 2.02 | 3 | | 1.979 | 2 |
| 0.15323 | 0.15308 | 212 | 1.969 | 6 | | 312, 212 | 1.961 | 25 | | | |
| 0.15727 | 0.15774 | 301 | 1.944 | 1 | | | 1.933 | 7 | | | |
| 0.16436 | 0.16478 | 23 $\bar{1}$ | 1.902 | 2 | | | 1.895 | 13 | | | |
| 0.16861 | 0.16835 | 032 | 1.877 | 6 | | | 1.870 | 18 | | 1.884 | 1 |
| 0.17061 | 0.17109 | 320 | 1.866 | 1 | | | 1.859 | 18 | | | |
| 0.17995 | | | 1.817 | 12 | * | | | | | 1.817 | 5 |
| 0.18319 | 0.18311 | 023 | 1.801 | 2 | | | 1.797 | 9 | | | |
| 0.18665 | | | 1.784 | 1 | | | | | | | |
| 0.19054 | 0.19121 | 231 | 1.766 | 2 | | | 1.762 | 18 | | 1.750 | 1 |
| 0.19542 | 0.19522 | 132 | 1.744 | 4 | | | 1.737 | 25 | | | |
| 0.20621 | 0.20632 | 140 | | | | | | | | | |
| 0.21272 | | | 1.671 | 5 | | | 1.689 | 13 | | 1.671 | 2 |
| 0.21591 | 0.21471 | 14 $\bar{1}$ | 1.659 | 2 | | | 1.645 | 7 | | | |
| 0.22411 | 0.22564 | 402 | 1.628 | 1 | | | 1.623 | 7 | | | |
| 0.22986 | 0.22922 | 203 | 1.608 | 1 | | | 1.600 | 7 | | | |
| 0.23988 | 0.23990 | 004 | 1.574 | 1 | | | | | | | |
| 0.25034 | | | 1.541 | 8 | * | | | | | 1.541 | 2 |
| 0.25297 | 0.25264 | 042 | 1.533 | 1 | | | 1.535 | 13 | | | |
| 0.27471 | 0.27418 | 40 $\bar{3}$ | 1.471 | 1 | | | | | | | |
| 0.27743 | 0.27739 | 223 | 1.464 | 1 | | | 1.463 | 5 | | | |
| 0.28134 | | | 1.453 | 2 | | | | | | 1.452 | 1 |
| | | | | | | | 1.423 | 3 | | | |
| 0.31132 | | | 1.382 | 6 | * | | 1.386 | 3 | | 1.382 | 2 |
| 0.31467 | | | 1.374 | 8 | * | | | | | 1.374 | 2 |
| 0.31589 | | | 1.372 | 4 | * | | 1.368 | 5 | | | |
| | | | | | | | 1.339 | 9 | | 1.287 | 2 |
| | | | | | | | 1.329 | 9 | | | |
| | | | | | | | 1.307 | 3 | | | |
| | | | | | | | + 32 lines | | | | |

* Lines from the internal standard quartz.

Monazite and bastnäsite are found together in the green veins but the two minerals are not seen in contact with each other. Monazite was probably formed under the same conditions as in Mountain Pass, California (Jaffe, 1955) where monazite formed until the phosphorus was used up after which bastnäsite crystallized.

| | These veins (GGU 20731) | Kvanefjeld | ASTM file no. 11-556 |
|---------------|--|---|-------------------------|
| a_0 | $6.780 \pm 5 \times 10^{-3} \text{ \AA}$ | $6.85 \pm 7 \times 10^{-2} \text{ \AA}$ | 6.77 Å |
| b_0 | $7.025 \pm 4 \times 10^{-3} \text{ \AA}$ | $7.04 \pm 3 \times 10^{-2} \text{ \AA}$ | 7.01 Å |
| c_0 | $6.471 \pm 4 \times 10^{-3} \text{ \AA}$ | $6.50 \pm 4 \times 10^{-2} \text{ \AA}$ | 6.43 Å |
| β | $103.35 \pm 7 \times 10^{-2}$ | $103.6 \pm 5 \times 10^{-1}$ | 103°10' |
| V_0 | 299.84 \AA^3 | 304.63 \AA^3 | |

Differential thermal analyses

Differential thermal analyses have been undertaken on bastnäsite and thorite. A micro-differential thermal analysis instrument of the type constructed by CHARLES MAZRERES was used. The instrument was calibrated using quartz and Al_2O_3 .

Thorite was run in air while bastnäsite was run in an atmosphere of CO_2 .

The resulting curves for bastnäsite and thorite from Nunasarnaq are seen in fig. 8 together with thorite from Langesundfjord, Norway for comparison and quartz run on the same instrument.

Bastnäsite shows endothermic reactions below 200° C and exothermic reactions between 250 and 400° C. The endothermic reaction is presumably due to loss of water and the exothermic reaction is presumably due to the reorganization of trapped electrons (see p. 37).

Thorite from Nunasarnaq shows endothermic reactions below 100° C and the exothermic reactions between 125 and 500° C and again between 700° C and 900° C. The endothermic reactions are presumably due to loss of water, while the lower exothermic reaction is due to the reorganization of trapped electrons (see p. 37). The higher exothermic reaction falls in the same interval as the crystallization of the metamict thorite (see p. 28), and it is therefore suggested that it is due to this crystallization.

The thorite from Langesundfjord, Norway has endothermic reactions below 100° C and exothermic reactions between 250 and 425° C and again between 850 and 950° C. Thus the two thorite minerals have similar endothermic and exothermic reactions. The thorite from Norway has more abrupt reactions.

ORCEL (1953) has made DTA-analyses on several metamict minerals and has found not only different temperatures for the endothermic and exothermic reactions in the same mineral from different localities, but also that the same mineral from one locality may have exothermic reactions in the same temperature interval as material from another locality has endothermic reactions.

Thermoluminescence analyses

In thermoluminescence analyses the light emission per second from a sample is registered as a function of temperature at a constant rate of heating (glow curve). The light emission can be due to chemical reactions, or to reorganization of trapped electrons which may be produced by radiation from radioactive isotopes or by mechanical deformation. The samples used here have been thoroughly cleaned and are not mechanically deformed.

The analyses were performed by V. MEJDAHL of the Atomic Energy Commission, Risø, using an instrument described by LIPPERT and MEJDAHL (1965). It has a mechanical light chopper in conjunction with a phase-sensitive detector. A kanthal plate serves as a heating pan with the material placed in a circular depression in the plate which is heated 10 to 15° C per second by a stabilized alternating current. The material was run in a nitrogen atmosphere to reduce spurious thermoluminescence.

Fig. 9 gives the glow curves of bastnäsite (natural), bastnäsite after heating to approximately 400° C, and exposed to 10⁶ rad cobalt 60 γ radiation, and thorite (natural). The natural bastnäsite has a peak between 150° C and 400° C with a maximum about 275° C, and thorite has a peak in the same interval with a maximum about 250° C. Bastnäsite, which was first heated to approximately 400° C and afterwards exposed to the γ radiation, has one great peak with a maximum about 200° C. This peak seems to include a small peak at 50 to 175° C and possibly a scatter of peaks in the same temperature range as that found for natural bastnäsite. The low temperature peaks, which are unstable at room temperature and therefore not found in the natural material, show that the bastnäsite is sensitive to radiation. This suggests a radiogenic origin of the 300° C peak in the natural bastnäsite. The peaks in natural bastnäsite and thorite fall in the same temperature interval as the exothermic reaction in the DTA-analyses (see p. 29) showing that this is presumably due to the reorganization of trapped electrons.

IX. COMPARISON WITH OTHER REGIONS

While uranium-bearing veins like the mineralized cracks described here have been known for a long time, thorium-bearing veins have only been known for the last few years. Thorium in veins is often associated with rare-earth minerals, as in the Ilímaussaq alkaline intrusion (SØRENSEN, 1962) and in some localities in the USA and in Brazil where the rare-earth-thorium veins occur around alkaline complexes, *e.g.* in Powderhorn, Colorado (OLSON and WALLACE, 1956), in Mountain Pass, California (OLSON *et al.*, 1954), and in Salmon Bay, Alaska (HOUSTON *et al.*, 1953 and MATZKO, 1955). Similar veins occur in Poços de Caldas, Brazil.

a) Comparison with veins in the Ilímaussaq intrusion

In the Ilímaussaq intrusion green veins are found which consist of ægirine felt with a little microcline, lepidolite, steenstrupine and analcime. The veins may have pseudomorphs after eudialyte. There are also veins composed of ægirine/acmite and/or arfvedsonite and minor amounts of analcime, natrolite, brown mica, neptunite, schizolite, steenstrupine, eudialyte pseudomorphs and rare eudialyte crystals. These veins are thought to be genetically connected with the *mise en place* of the lujavrites. A later albitization may have attacked these veins transforming microcline into albite. At the same time steenstrupine, schizolite, sphalerite, lepidolite and neptunite were formed.

The green veins in the Ilímaussaq intrusion differ first of all from the green veins described here in containing the undersaturated minerals analcime and natrolite. These minerals are absent in the veins outside the intrusion.

Monazite and bastnäsite have both been found in the green veins outside the intrusion, but only monazite has been found in the veins inside the intrusion. This may be connected with the extreme rarity of CO₂-bearing minerals in Ilímaussaq. Bastnäsite has only recently been discovered as a minor constituent in the green lujavrites of Ilímaussaq.

Steenstrupine, a common mineral in the green veins in the intrusion, has not been identified in the veins described here. However a brown strongly radioactive powder is found in pseudomorphs which may be after steenstrupine. This is in accordance with the observation that

steenstrupine in the intrusion may have inclusions of small isotropic grains of thorianite (BUCHWALD and SØRENSEN, 1961) or be altered to a brown and black material of uncertain composition (SØRENSEN, 1962 p. 231).

Both inside and outside the intrusion the green veins are succeeded by the formation of albititic veins or by an albitization of the green veins.

Calcite has been found in the hydrothermal veins in and around the intrusion. Outside the intrusion calcite veins are younger than the albititic veins; no age relation has been established between the calcite veins and the albititic veins in the intrusion. It is only known that the calcite veins there are younger than the naujaite, but these veins are very rare.

Quartz veins, which are common outside the intrusion, have only been found in the alkali granite in the uppermost part of the intrusion.

The late coatings of iron-manganese oxides may be compared with the red zones in the naujaite in the Ilímaussaq intrusion (USSING, 1912 p. 63 and 77). In these zones the naujaite is filled with hematite and fluorite while green garnet and albite may occur. Aegirine and arfvedsonite may be replaced by chlorite while sodalite and nepheline are converted to epidote, "spreustein" and green "gieseckite-like" pseudomorphs. The feldspar mostly remains relatively unaltered. Where alteration is most intense the rock is transformed throughout to a zeolitic aggregate which is filled with hematite and fluorite. These zones may have a regular dyke-like form generally with a WSW-ENE trend. They intersect the lujavrite veins in the naujaite.

USSING suggested that the transformation may have proceeded from vertical fissures. At first emanations containing fluorine and iron saturated the adjacent rocks with fluorite and hematite; later, at lower temperatures, water vapour and hot water have penetrated through the fissures and led to the formation of the zeolites.

Both inside and outside the Ilímaussaq intrusion the brown albititic veins as well as the green veins were probably formed from their respective fluids. The difference in the host rocks inside and outside the intrusion could explain why analcime and natrolite are restricted to the veins in the intrusion.

b) Comparison with veins in other intrusions

In the Powderhorn alkaline complex there are veins and mineralized shear zones with calcite, dolomite, siderite, ankerite, quartz, barite, pyrite, sphalerite, galena, hematite, goethite, apatite (a rare-earth variety), alkali feldspar, aegirine, sodic amphibole, phlogopite, zeolites etc. In these veins rare-earth minerals such as bastnäsite, synchisite, cerite (?)

and xenotime (?) are found. The veins are often radioactive due to a thorium content and thorite and thorogummite have been identified.

In Poços de Caldas in Brazil lenticular deposits occur with a high content of thorium and rare-earth elements and a very low content of uranium, believed to occur in zircon which probably was an accessory mineral in the original country rocks (WEDOW, 1961; TOLBERT, 1966). The radioactive zone is a mixture of highly decomposed nepheline syenite, limonite and magnetite. Much of the thorium is found in disseminated grains of thorogummite and allanite. The rare-earth elements occur chiefly in allanite and bastnäsite. Generally the content of thorium makes up more than 1 % of the rock, the total rare-earth oxides more than 5 % and the uranium 0.00 X to 0.0 X %.

At Bastnäs, Sweden there are veins with rare-earth minerals but without thorium minerals (GEIJER, 1963); this is also the case in the Gallinas Mts., New Mexico (GLASS and SMALLEY, 1945).

Cerium minerals such as bastnäsite, cerite, törnebohmitite, orthite and magnesium orthite are found at Bastnäs. The cerium ore and its gangue have apparently replaced dolomite which occurs as beds inter-banded with quartz-banded iron ore. Commonly associated minerals are chalcopyrite, molybdenite, bismuthite and magnetite. GEIJER suggests that the rare-earth mineralization is due to fractionation and concentration processes at depth in connection with the metasomatic action which took place when the Leptite Formation was folded and intruded by the Svecofennian granite.

There are also examples of thorium-mineralized veins without rare-earth minerals, *e.g.* south of the Igaliko Complex (HANSEN, 1962) and in the Wet Mts., Colorado, USA (CHRISTMAN *et al.*, 1959).

South of the Igaliko Complex there are found veins which in the centre consist of quartz and albite with aggregates of fine-grained ægirine. These aggregates, which are up to 1 × 5 cm, consist of randomly orientated needles of ægirine. The border zones consist in some places of 2–3 cm thick zones of ægirine felt; in other places there are ægirine prisms up to 3 cm long and 1 mm broad with the long direction of the crystals perpendicular to the vein direction, embedded in a quartz-feldspar matrix. The veins give up to 0.1 mR/h. These veins are found in granite and in a tinguaitite dyke which they cross. Under the microscope it is seen that the veins, in addition to ægirine, quartz and feldspar, consist of calcite and hematite. The ægirine often has border zones of acmite. Ægirine may be partly transformed into chlorite or be replaced by calcite. The quartz is interstitial between the other grains and is here, as in the veins on the Ilimaussaq peninsula, a late-formed mineral. No autoradiographic analysis has been made of the rock but the radioactivity is thought to be connected to radioactive material adsorbed on the hematite.

In the Wet Mountains the principal thorium mineral is thorite which generally occurs in zones of feldspathized rocks. Iron oxides are abundant and occur as scattered crystals, aggregates of crystals and as thin films around other minerals. Other associated minerals are quartz, carbonate minerals, sulphides and a little fluorite.

c) The mineralized cracks

Deposits like the mineralized cracks are very common. They occur for example in Poços de Caldas, Brazil. Here hydrothermal deposits of zircon and baddeleyite are found in fractures in deeply decomposed nepheline syenites containing the zirconium-bearing minerals rosenbuchite, eudialyte, lāvenite and eucolite. (FRANCO and LOEWENSTEIN, 1948; TOLBERT, 1966). The zirconium and uranium in the fractures are considered to have been formed at the expense of zirconium and uranium leached out from the zirconium silicates in the country rocks. The uranium is mostly disseminated and may substitute for zirconium in zircon. The only uranium mineral identified is meta-autunite. A late oxidation and enrichment has up-graded the uranium content and possibly the zirconium content of some of the deposits making them of economic value.

X. CHRONOLOGY AND ORIGIN

The mineralized zones occur in Precambrian granite, sandstone, lavas and dolerite dykes. In section III it has been shown that the veins are formed in tension joints.

The cracks mineralized with hematitic material are found as inclusions in the brown albititic veins, and material from the latter may be further albitized and cut by carbonate and quartz veinlets. In all the veins there may be coatings of late iron-manganese oxides.

The veins generally strike NE-SW but they may show local deviations from this direction. The relation between the different fractures are best seen along the shore south of the headland at Sitdlisit. Here two NE-SW dolerite dykes and a mineralized zone split into a series of smaller parallel dykes which follow NNE-SSW fractures in an E-W zone of cracks and joints. On the other side of this zone the small dykes coalesce to form two thick dykes and one mineralized zone. The NNE-SSW dykes and mineralized zones are displaced slightly by small NE-SW fractures. Very late fracturing also occurs inside the Ilimaussaq intrusion (see p. 39).

From the above it is concluded that at least three generations of joints and fractures can be recognized. First joints in the granite and sandstone were opened in NE-SW and E-W directions and succeeded by the emplacement of dolerite dykes. With a reopening of the fractures, particularly those striking NE-SW, the mineralized zones of cracks and joints, the brown albititic veins and the green veins were developed. Sometimes the fluids were emplaced successively in the same joint giving composite veins. These veins may be albitized and cut by thin late calcite veins. During a third opening the quartz veins were formed. All the veins may have a brown to black coating of late iron-manganese oxides.

It is natural to suggest that the radioactive material has come from the neighbouring Ilimaussaq intrusion from which similar veins have been described (see p. 38). The author has traced the veins described here almost to the very contact of the intrusion.

In the Ilimaussaq intrusion as well as in the green and brown albititic veins, thorium predominates over uranium. In the intrusion the Th/U ratio averages 4, while in the veins outside the intrusion it is 15 (see p. 17).

Temperature and pressure

None of the minerals found in the veins can be used as indicators of temperature or pressure of formation of the veins. However, something can be said about the conditions of crystallization.

The veins were formed relatively near to the surface since the veins are fracture controlled and alteration of the rocks has been limited to recrystallization of quartz. Only in one place has actinolitic hornblende been found. Open spaces in the veins often occurred and many short, irregular veinlets were formed. This suggests a low temperature and pressure of formation.

The green veins have the same major minerals as the green veins in the Ilímaussaq intrusion, with the exception that the undersaturated minerals analcime and natrolite have not been formed in the veins in the acid country rocks outside the intrusion. SØRENSEN (1962) has suggested a temperature of formation for the green veins inside the intrusion of about 400° C. As the mineralogy of the veins in and around Ilímaussaq is practically identical, a similar temperature of formation may be postulated for the veins outside the intrusion. Arguments in favour of this statement are:

1) The microcline which has been found in some samples of the green veins is the low temperature form displaying the penetration twinning that is common in per-alkaline rocks. This penetration twinning is also found in low-grade metamorphic schists (BARTH, 1959) where it is thought to have formed at such a low temperature (below 300° C) that the triclinic potash feldspar formed directly (*cf.* discussion by SØRENSEN, 1962 p. 224).

2) CHRISTOPHE-MICHEL-LÉVY (1954) and WYART (1954) have synthesized ægirine in the temperature interval 250° C to 500° C at 520 to 570 bars water pressure. They did not succeed in forming ægirine below 200° C to 250° C.

The late albititic material may have been formed from the same type of fluids that formed the analcime-natrolite and albititic veins in the Ilímaussaq intrusion. These fluids, it is suggested, were given off from the lujavrite magma in the Ilímaussaq intrusion during or late in its solidification at a temperature of 400° C or less (SØRENSEN, 1962).

The late iron-manganese oxides may have been formed from the same fluids which have given the red zones in the naujaite.

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Plate 1.

- Fig. 1. GGU 20709. $\times 25$. one nicol. Green vein composed of small orientated ægirine needles with subordinate amounts of albite and microcline. The grey spot in the middle is a hole after thorite.
- Fig. 2. GGU 20714. $\times 45$. crossed nicols. Green vein composed of ægirine, albite and microcline with bastnäsite (B). The grey spot in the upper left side is a hole.
- Fig. 3. GGU 20717. $\times 35$. one nicol. Composite vein with aggregates of ægirine in a matrix of orientated late albite. The ægirine is partly altered to acmite.

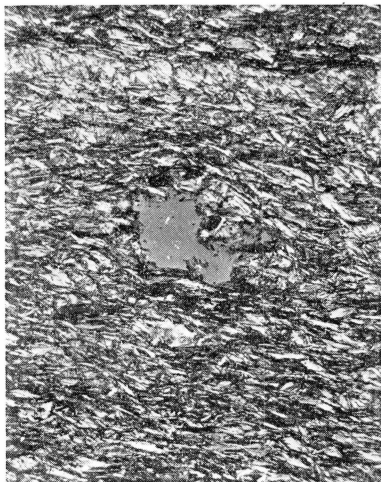


Fig. 1.



Fig. 2.

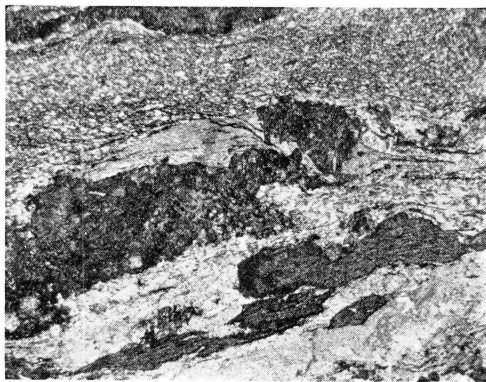
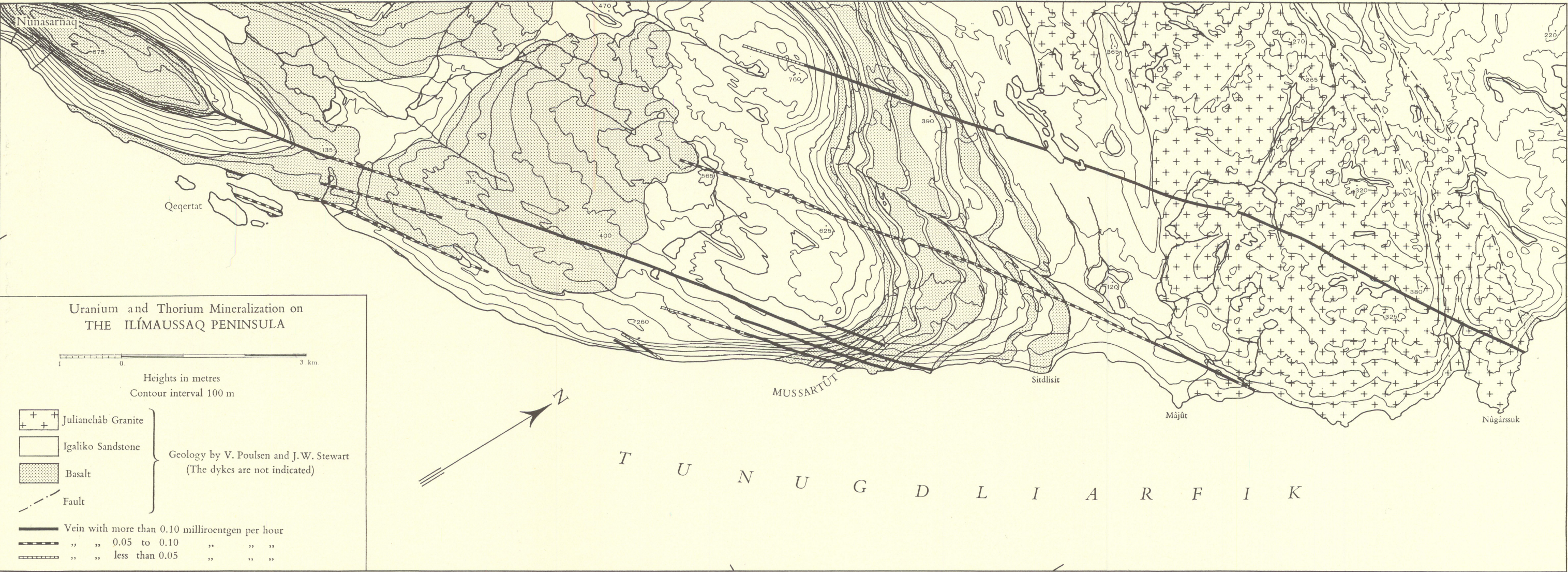


Fig. 3.

GRØNLANDS GEOLOGISKE UNDERSØGELSE
THE GEOLOGICAL SURVEY OF GREENLAND

MEDDR GRONLAND BD 181 NR 8 (JOHN HANSEN)

PLATE 2



GRÖNLANDS GEOLOGISKE UNDERSØGELSE
THE GEOLOGICAL SURVEY OF GREENLAND

MEDDR GRÖNLAND BD 181 NR 8 (JOHN HANSEN)

PLATE 3

