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Field observations on the kakortokites of the Ilímaussaq intrusion, South Greenland, including mapping and analyses by portable X-ray fluorescence equipment for zirconium and niobium

by

H. Bohse, C. K. Brooks and H. Kunzendorf

Contribution to the mineralogy of Ilímaussaq no. 25

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GRØNLANDS GEOLOGISKE UNDERSØGELSE
RAPPORT NR. 38

FIELD OBSERVATIONS ON THE KAKORTOKITES OF THE ILÍMAUSSAQ INTRUSION, SOUTH GREENLAND, INCLUDING MAPPING AND ANALYSES BY PORTABLE X-RAY FLUORESCENCE EQUIPMENT FOR ZIRCONIUM AND NIOBIUM

by

H. Bohse, C. K. Brooks and H. Kunzendorf

Contribution to the mineralogy
of Ilímaussaq no. 25

With 19 figures, 3 tables
and 1 map

1971

Abstract

Detailed mapping, sample collection and studies of zirconium and niobium distributions in the kakortokites of the Ilímaussaq intrusion have been carried out.

Each of the 29 major rhythmic units has been mapped and a comprehensive sample collection made for further work. A horizon caused by slumping of the unconsolidated crystal mush has been recognised and it has been shown that a number of large inclusions are confined to a single horizon. The slumped rocks indicate that the depth of unconsolidated material was of the order of 20 m (compared with only a few metres for other intrusions discussed in the literature) with a maximum angle of rest of some 20°. Faults, fine-scale layering, trough banding, the border pegmatite and later intrusions are described.

A programme of field and laboratory determinations of Zr and Nb has delimited their distribution within these rocks and allowed a first estimate of the total, easily-accessible quantities of these elements to be made.

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CONTENTS

INTRODUCTION

The work described in this report forms part of a project under the general direction of Professor Henning Sørensen for the detailed re-mapping and investigation of the Ilímaussaq intrusion of South Greenland, with particular reference to potentially economic mineral deposits.

Field work was initiated in 1968 on the southern part of the intrusion which consists largely of strongly-layered eudialyte-nepheline-syenites, called kakortokite (Ussing, 1912), in order to gain a detailed picture of the attitudes of the layering and other igneous structures and to assess the distribution of eudialyte and other minerals of possible economic value. This latter part of the work was carried out in close co-operation with the concession holders, Aktieselskabet Dansk Svovlsyre- og Superphosphat-Fabrik (D.S.S.F.) who carried out large-scale sampling and have kindly placed material from these collections at our disposal.

Work was continued in the summer of 1969 and included analyses made by portable isotope-excited X-ray fluorescence equipment. Although these measurements are regarded only as preliminary, the instrument performed so well under field conditions that it is considered worth-while to include the results in this report. Field work was completed in the summer of 1970 when the X-ray fluorescence measurements were extended to the rare earth elements La, Ce, Nd and Pr. Results of these determinations are not reported here but will be incorporated in a later report. The experimental aspects of a similar laboratory method are the subject of a separate paper (Kunzendorf & Wollenberg, 1970).

We intend to follow up the field work described in this report with a detailed laboratory examination of the rocks. A collection of about 100 carefully-taken samples representing the entire exposed vertical sequence has been made and it is our intention to investigate the chemistry of the major minerals (nepheline, alkali feldspar, eudialyte, aegirine, and arfvedsonite) with particular reference to any vertical variations which may exist in an effort to evaluate changing conditions in the magma from which these minerals were precipitated.

Fig. 1. Vertical air photograph of the area immediately south of Kangerdluarssuk showing layering in the kakortokites (reproduced with the permission of the Geodetic Institute, Copenhagen).

PREVIOUS WORK

A detailed history of work on the Ilímaussaq intrusion, starting with its discovery in 1806 by Giesecke up to almost the present time, has recently been written by Sørensen (1967). The most important contributions relating to the kakortokites are those of Ussing (1912) and Ferguson (1964). The latter author's interpretation of the intrusion is the one most favoured today and suggests that the kakortokites which are characterised by a striking layered structure, (seen in the air photograph, fig. 1 and also in fig. 2) were formed by bottom accumulation of minerals from a peralkaline undersaturated magma, rich in certain components, notably zirconium. The kakortokites are therefore arfvedsonite-eudialyte-aegirine-nepheline-alkali feldspar cumulates and their cumulate nature is clearly shown by their textures. Simultaneously with the formation of the kakortokites the remarkable poikilitic rocks known as naujaites were formed by flotation of sodalite crystals as the primary phase to the top of the magma chamber where the other liquidus phases subsequently crystallised to the poikilitic matrix of the rock. The naujaites have been brecciated by the intrusion of lujavrites, material thought to represent the residual liquids quenched by abrupt pressure release. The lujavrites are fine-grained rocks with a high proportion of arfvedsonite and/or aegirine, often with a strongly schistose texture.

A notable feature of the kakortokites is that, although a careful search was made by Ferguson (1967) using optical and, in the case of nepheline, X-ray techniques, no cryptic variation (except possibly in the nepheline) was found in the cumulus minerals of this sequence which consists of some 400 m thickness of layered rocks. Minor variations in certain ratios of trace to major elements (e.g. Rb/K and Sr/Ca) with height in the kakortokites strongly suggestive of progressive fractionation, have however been noted (Ferguson, 1970 a & b). This suggests that crystallisation took place under eutectic conditions.

The work on minerals presently being carried out using the electron microprobe is designed to check this observation using more sensitive methods and a more complete range of samples than those of Ferguson. It should be born in mind that although a property of eutectic crystallisation is that the major elements do not undergo fractionation, there is no such restriction on minor and trace elements (Turner & Verhoogen, 1960, p. 162) and one would therefore expect regular variations in these elements as a function of height in the sequence, a feature which may conceivably have significant bearing on the economic uses of these minerals whose minor elements will probably represent valuable by-products. Such a variation was, as noted above, observed by Ferguson (1970a) but the effects were partially masked by variations in modal composition and would be expected to show up much more clearly in the mineral series.

Other important contributions to our knowledge of Ilímaussaq have been made by Ferguson & Pulvertaft (1963) who discussed the layering, and Sørensen (1969) who compared Ilímaussaq with the rather similar Lovozero intrusion in the USSR and critically examined earlier theories for the origin of such rocks. More recently two papers by Ferguson (1970 a & b) give estimates of average compositions of the various rock types together with details of chemical differentiation trends and a wealth of additional observations on the kakortokites including petrology, petrofabrics and geochemistry of the rocks, much of which is also to be found in his Ph.D. thesis (1967).

Apart from the earlier scientific studies referred to above, two previous investigations of the economic potential of these rocks have been made. The first was by Steenstrup in 1888 and 1889 and the second by Bøgvad in 1946, both on behalf of Kryolitselskabet Øresund A/S (see Sørensen, 1967, p. 12, Allen & Charsley, 1968, p. 128). At those times no use could be found for the kakortokites and the work was not pursued.

THE LAYERING IN THE KAKORTOKITES

Owing to the persistence and clarity of individual layers of the kakortokites, these may be mapped in the same way as if one were dealing with sedimentary layers (which indeed cumulate rocks are, although not in the ordinary sense). This was attempted by Ferguson (1964) although more detailed work has shown that the attitude of the layering shown on his map is incorrect in detail.

We have used the following terminology: each distinctive horizon whether it be black, red or white kakortokite is termed a 'layer', while each single cycle of layers is known as a 'unit'. The layering is caused solely by variations in the modal amounts of cumulus minerals, i.e. the black layers are rich in arfvedsonite, the red layers in eudialyte and the white layers in alkali feldspar and nepheline. A unit is characteristically composed of a black, a red and a white layer in ascending order. However, any one of these may be absent in certain cases.

Although the layering stands out clearly from a distance (fig. 2) it is not always so obvious at close quarters. Furthermore, incipient, poorly-developed layers occur at certain horizons which give rise to doubts about the exact number of units. These difficulties may be overcome by reference to photographs taken with a polaroid camera from a distance. In general the layering is less regular in detail than we had expected from the impression gained from Ferguson (1964). In particular some layers are faint while others are strongly marked due to differences in the degree of

Fig. 2. The cliffs of Kringlerne as seen from Kangerdluarssuk with the units numbered as described in the text. The height from unit +1 black to unit +13 white is approximately 110 metres.

sorting among the cumulus minerals. In addition there are pronounced thickness variations between layers, differences in the nature of the contacts between layers and differences in the texture and grain size. These factors were all found to be useful in mapping and with practice we found it possible to recognise many layers by certain characteristic features.

At an early stage in the work a very prominent unit was selected for use as a marker horizon. This unit consists of a very dense black basal layer, separated from the underlying white layer by a very sharp contact and showing strong lamination; a thick very red layer with a saccharoidal texture (due to a very high abundance of equidimensional eudialyte) and clearly visible from some distance away; and a rather thick white layer with a relatively poor lamination and a high content of yellow rinkite (which characterises the white layers in general). Further details of this unit, known as unit 0, are given in table 3. This unit was first observed where it outcrops at the foot of the Kringlerne cliffs in a gulley just west of the large inclusions seen in fig. 2 and figured by Sørensen (1958, p. 14), see also locality map, fig. 3. Unit 0 was used as the datum to which all other units are referred. It may easily be followed with only minor exposure breaks along the Kringlerne cliffs, in which it occurs at varying heights, to Laksetværelven which it crosses just above the boulder fan where it joins Lakseelv, and may be seen to dip about 20° in a north-easterly direction. This dip is similar to the gradient of Laksetværelven and unit 0 may consequently be followed up this valley for a considerable distance. Unit 0 is not seen east of Laksetværelven as it has dipped beneath the alluvium of Laksedal.

Once the outcrop of the marker horizon was established it was a relatively easy task to map in the other units. There were found to be 17 units above unit 0, labelled +1 to +17, and 11 below (−1 to −11). Fig. 2 shows the numbered units as seen in the Kringlerne cliff sections. The lower units are only seen at the western end of the area below Kringlerne and are somewhat difficult to map owing to scree on the slope. Just as in the case of unit 0 in Laksetværelven, the topographic dip corresponds closely with the dip of the layers and some horizons are exposed over quite large areas. This demonstrates the need for detailed mapping before sampling for laboratory work is carried out: when the stratigraphy is inadequately known traverses may transect only a limited number of units or sample the same succession twice and not give adequate representation of the whole series.

Details of the sampled profile whose location is shown in fig. 3 are given in table 1. It is believed that these observations are applicable to the whole intrusion as there is no evidence for variations along the strike of the layers; indeed certain facts (such as the ZrO_2 measurements on unit 0 reported below) support this conclusion. A few points beyond those given in table 1 are worthy of additional comment.

Dense black rocks, occasionally with augen-like patches rich in eudialyte, outcrop over large areas below Kringlerne in the innermost part of the fjord, and at the outset of our investigations had received little attention and were regarded as problematical in nature and origin. We now believe that these rocks represent

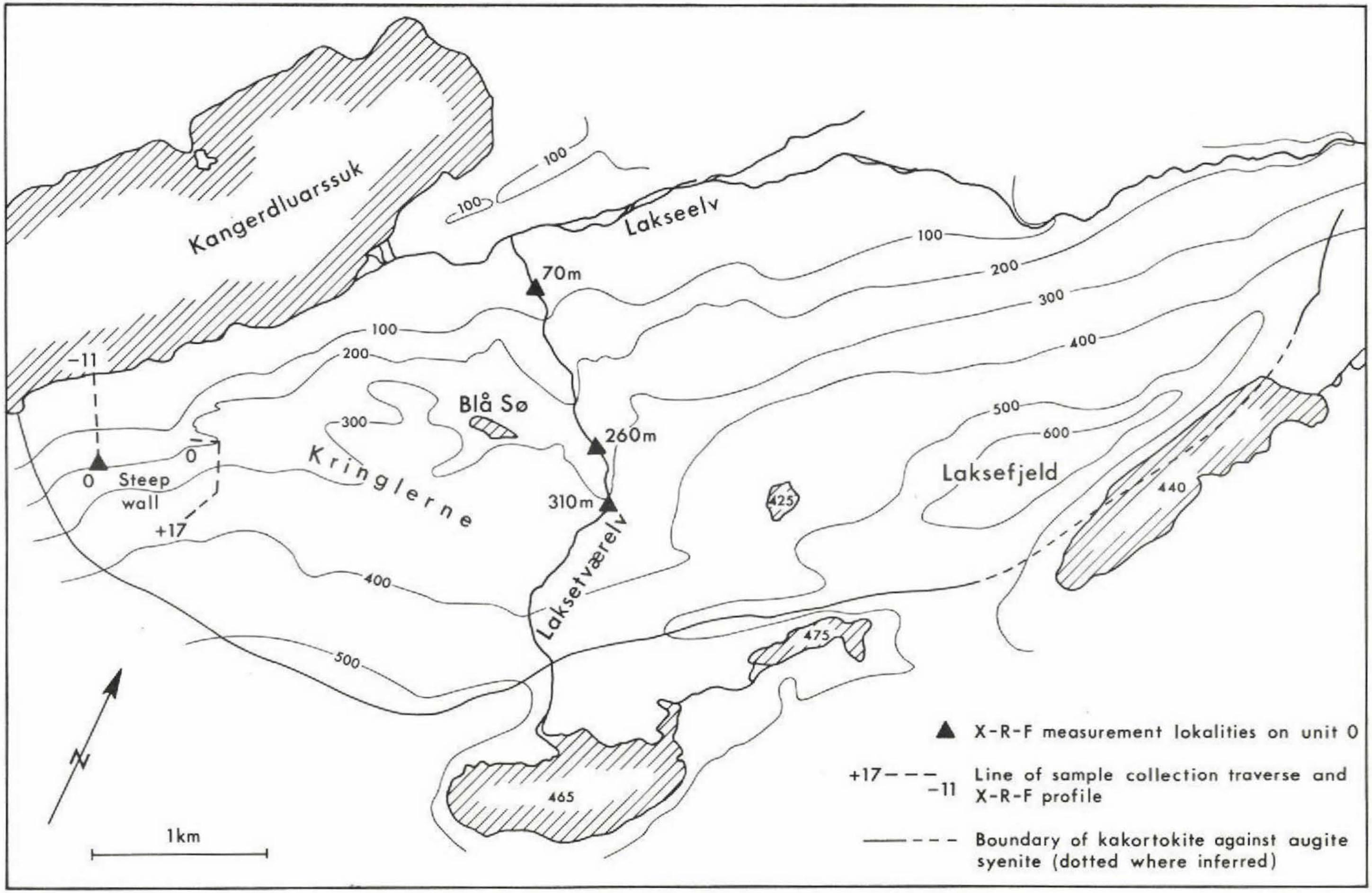

Fig. 3. Map showing location of sample traverse and other features referred to in the text.

Table 1. Description of the kakortokite succession.

Layer number	Thickness (metres)	Remarks
unlayered upper part	ca. 200	Layering inconspicuous or faint black layers visible only from a distance. Arfvedsonite acicular rather than prismatic as lower down.
+ 17 white	?	
+ 17 red	absent	
+ 17 black	?	Well-developed feldspar lamination, weak lineation of lath-shaped arfvedsonite in dip direction.
+16 white	9	Lower part shows well-developed fine-scale layering on a scale of about 1 cm due to alternations of arfvedsonite and eudialyte-rich layers.
+16 red	3.5	Shows a characteristic fissility breaking up into flag-stones of 3-6 cm thickness.
+16 black	?	
Green Sill	ca. 3	
+15 white	10	
+15 red	absent	
+15 black	2.5	Very poorly developed i.e. not particularly arfvedsonite-rich.
+14 white	7	
+14 red	absent	Upper part of black layer rather rich in eudialyte but no distinct red layer developed.
+14 black	2	Only slightly better developed than +15 black.
+13 white	6	
+13 red	0.5	Poorly developed.
+13 black	1.5	Poorly developed
+12 white	4	
+12 red	0.1	

Table 1. (continued)

+12 black	1	Strongly developed with clear lamination. Sharp boundary with +11 white.
+11 white	3	Spotty appearance. Arfvedsonite clearly intercumulus, eudialyte almost absent.
	0.5	Layer unusually eudialyte-rich.
	3	Normal white type.
+11 red	0.5	Rather arfvedsonite rich.
+11 black	1	Not strongly developed.
+10 white	4	
+10 red	absent	Boundary between white and black somewhat richer in eudialyte but no proper red layer.
+10 black	1	Very black with sharp boudary to +9 white. Strong lamination.
+ 9 white	8	A thin reddish layer occurs about 1 m below top of unit.
+ 9 red	1	Rich in arfvedsonite.
+ 9 black	0.5	Very black and well laminated.
+ 8 white	5	Poor in eudialyte in the upper 3 m.
+ 8 red	absent	Eudialyte content rises but scarcely enough to produce a distinct red layer.
+ 8 black	5	Rich in eudialyte – either red kakortokite rich in arfvedsonite or black rich in eudialyte.
+ 7 white	6	
+ 7 red	1	
+ 7 black	1	One of the blackest layers – very arfvedsonite rich.
+ 6 white	6	Very poor lamination
+ 6 red	1	
+ 6 black	1	Rich in eudialyte therefore not an especially strong black layer.

Table 1. (continued)

+ 5 white	4	
+ 5 red	0.5	Poor in eudialyte.
+ 5 black	1	Poor in arfvedsonite.
+ 4 white	5	Rich in eudialyte.
+ 4 red	absent	
+ 4 black	1	Well developed.
+ 3 white	20	Thickest layer. Contains here and there two weak black layers. Many inclusions.
+ 3 red	1	
+ 3 black	1	Very black.
+ 2 white	8	
+ 2 red	0.5	
+ 2 black	0.5	Very black well developed layer.
+ 1 white	6	
+ 1 red	0.3	Poorly developed.
+ 1 black	0.5	Poorly developed.
0 white	4	
0 red	2.1	*see detailed description in table* 2.
0 black	0.7	
− 1 white	2.5	Sharp boundary to overlying black. Large microcline crystals.
− 1 red	1	Not well developed, almost a white kakortokite.
− 1 black	0.5	Poorly developed, weak lamination, large microcline crystals.
− 2 white	3	Large microcline crystals.
− 2 red	1	Poorly developed.

Table 1. (continued)

− 2 black	0.5	Poorly developed.
− 3 white	3	Rather rich in aegirine.
− 3 red	absent	
− 3 black	0.5	Weak layer – almost unnoticeable except from a distance. Long arfvedsonite laths (ca. 1.5 cm).
− 4 white	6	Rather eudialyte-rich in top metre, below this a further metre of eudialyte-rich material but containing poikilitic arfvedsonite enclosing nepheline and eudialyte. Lower 4 m poor in eudialyte but containing poikilitic arfvedsonite giving the rock a spotty appearance.
− 4 red	0.5	Well-developed layer with large microcline laths and poikilitic arfvedsonite. Sharp transition to −4 black.
− 4 black	1	Thin microcline crystals, high nepheline content with crystals up to several mm across. Very dark and well laminated, similar to layer 0 black. Sharp boundary with layer −5 white.
− 5 white	4.5	Poikilitic arfvedsonite, rich in eudialyte.
− 5 red	2	Strong layer rich in eudialyte. Arfvedsonite not poikilitic.
− 5 black	0.5	Normal with well-developed lamination. Sharp contact with underlying layer.
− 6 white	4	Distinctly coarser that the overlying layers.
− 6 red	1	Similar to −5 red.
− 6 black	0.5	Similar to −5 black but a little darker.
− 7 white	8	Coarse-grained and poor in eudialyte.
− 7 red	absent	
− 7 black	1	Rather weakly developed with large well-formed microcline tablets.
− 8 white	6	Coarse with low eudialyte content (similar to −7 white).

Table 1. (continued)

− 8 red	1	Coarse and not especially eudialyte-rich. It was from this horizon that Kryolitselskabet Øresund A/S collected a sample. Sharp boundary to underlying white layer.
− 8 black	absent	
− 9 white	5	Coarse. Also collected by Kryolitselskabet Øresund A/S and D.S.S.F. sample no. H. 2.
− 9 red	1	Very eudialyte-rich. D.S.S.F. sample no. R. 1.
− 9 black	0.2	Very weakly developed and rich in microcline. Shows sharp boundary to −10 white.
−10 white	2	Very coarse grained.
−10 red	absent	
−10 black	1	Well-developed lamination, very coarse. Sharp boundary to −11 white. D.S.S.F. sample no. S 1 and no. S 2.
−11 white	>2	Coarse-grained with large microcline and arfvedsonite crystals. D.S.S.F. sample no. H 1.

1) The remarks regarding grain size, etc. are intended to record impressions gained in the field; no detailed measurements have been made.
2) Transitions between layers are in every case gradational over a distance of several centimetres except where otherwise noted as being sharp.
3) D. S. S. F. sample no. R 2 lies outside the numbered units, close to the marginal pegmatite. The rocks at this point are finely banded (fig. 6) and appear unusually rich in eudialyte. A drill hole sunk to 39 m from this point has not yet been examined in detail but can be seen also to be finely layered and rich in eudialyte.

material which slumped down a steep surface of deposition in the magma chamber while the crystal pile was still unconsolidated. These rocks are discussed in some detail below.

Previous workers have commented on the large inclusions of augite-syenite and naujaite within the kakortokites (one is clearly seen in fig. 2). Our mapping has demonstrated that these inclusions are almost entirely confined to a single horizon, namely unit +3, and therefore represent a single large-scale roof collapse. Alteration is widespread in these inclusions, epidote being abundantly developed. They also appear to be extensively albitised and in places are cut by albitic veins containing acicular aegirine in small (ca. 1 cm diameter) radiating aggregates, deep purple

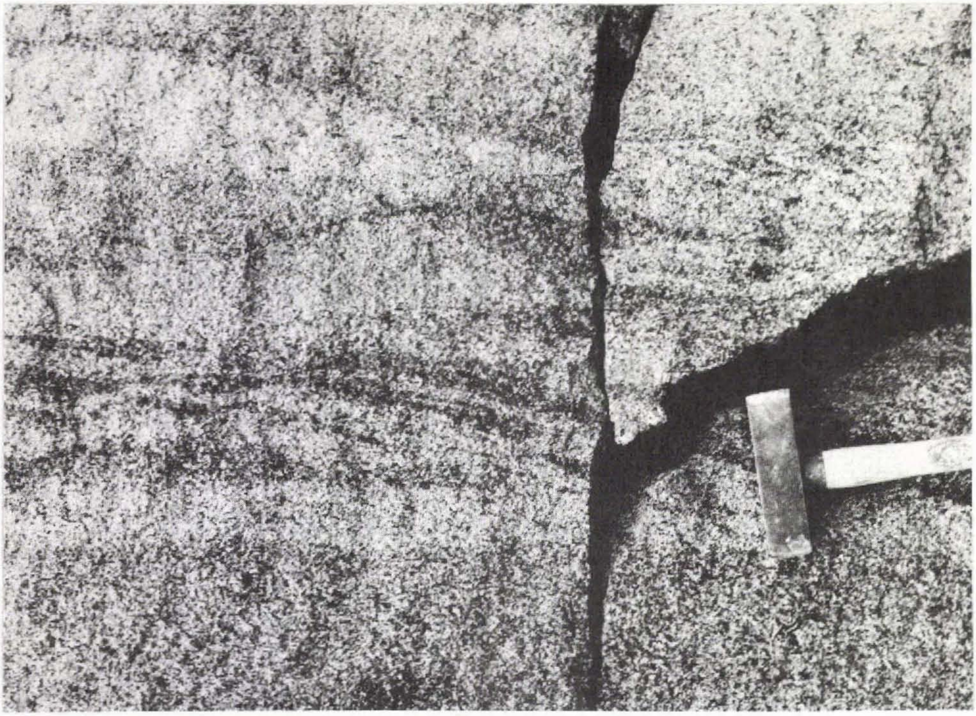

Fig. 4. Weathered surface of kakortokite at side of 'Blå Sø' showing streaky features believed to be due to magmatic currents.

fluorite, prehnite and other minerals. The inclusions are frequently rimmed by agpaitic pegmatites up to half a metre wide. Small inclusions of sodalite-foyaite have also been recognised in addition to the large one shown on the map. A number of streaky, apparently sedimentary features, also occur in the kakortokites round about this horizon (fig. 4), some resembling current bedding. These are interpreted as results of turbulent currents in the magma-chamber set up by the large settling blocks. Above unit 3 no features of particular note occur until unit +16 which is extremely distinctive and was mentioned by Ferguson (1964, p. 29). A thick, unusually eudialyte-rich layer similar to that of unit 0 but showing rather distinct fine-scale layering ('inch-scale layering') due to concentrations of dark minerals in thin horizons forms the highest layer exposed over a large area (higher units are preserved only in the extreme eastern part of the area and as a tiny erosional remnant of unit +17 on Kringlerne). This red layer of unit +16 is underlain by a green-coloured porphyry sill 3-6 m thick whose contact to the kakortokite is characterised by pegmatite with radiating aggregates of aegirine needles up to 6 cm in diameter. The phenocrysts in this sill are alkali feldspar while the green colour of the very fine-grained groundmass suggests a high aegirine content. This rock has a splintery jointing and the joint surfaces are frequently coated with a layer of neptunite. The pegmatitic margins contain purple fluorite and specks of molybdenite (in some specimens) as noteworthy features. Dykes of similar material can be seen to be continuous with this sill and are probably feeders, while in the eastern part of the area a sill of agpaitic pegmatite approximately 4 m thick and showing a zonal structure parallel to the margins underlies this sill, but is absent on Kringlerne.

The outcrop of unit + 16 and its underlying sill to the east of Laksetværelven dips in the north-easterly direction already referred to and disappears beneath the exposed rocks higher up Laksedal. All the rocks east of this horizon therefore lie at a higher stratigraphic level than unit +16. These rocks rapidly lose their clearly-marked layered structure, only indistinct dark layers being visible from a distance. They are relatively fine-grained with acicular ferromagnesian minerals rather than the prismatic ones of the lower rocks. In places pegmatitic pockets are developed which contain various minerals including albite, felted aegirine, lithium mica, sphalerite, astrophyllite and minor sulphur-yellow genthelvite.

Above the kakortokites are found large augite-syenite masses which rest conformably on the layering so far as can be determined, and are wrapped by finely schistose green lujavrites. The inclusions occasionally show marked layering and are usually intensely altered. Zones of alteration pass outwards into the kakortokites and are shown on the map, being marked in the field by a strong rusty weathering. Layer 16 red may be seen to be affected by this alteration and both fresh and altered specimens have been taken for further study. Farther up Laksedal these zones of alteration become more extensive and characteristic minerals such as epidote, specular hematite, green garnet, calcite, fluorite and ilvaite are abundant. This alteration is closely similar to that observed in the inclusions described earlier. In the few places where the transition kakortokite to overlying lujavrite can be observed it is seen to be rather gradual; the kakortokite decreasing in grain-size and increasing in aegirine content over a distance of some metres until the rock is a typical green lujavrite. The last indistinct kakortokite unit contains a red eudialyte-rich layer and the overlying lujavrite appears to be conformable to the kakortokite layering. A very similar transition is observed in the small kakortokite area north of Lakseelv as discussed below in connection with the fault which is believed to follow the line of this river.

ORIGIN OF THE LAYERING

The layering has attracted much attention in the past and several writers have suggested mechanisms for its formation. Both Ussing (1912) and Ferguson (1964 and 1967) have suggested that it was caused by intermittent volatile release caused by surface volcanism, but Sørensen (1969) who reviewed previous literature on both Ilímaussaq and Lovozero considered this mechanism to be unlikely.

It is not within the scope of this report to speculate on the origin of the observed features but our observations have led us to certain conclusions which it may be worth-while to mention briefly here.

We have considered the probable effects of intermittent gas release by volcanic activity and agree with Sørensen (1969) that it does not adequately explain the facts. It seems unlikely, though not impossible, that such a process would give rise to the remarkably regular sequence. Furthermore it would be expected that such a rapid fall in pressure would have additional effects, for instance, rapid crystallisation leading to fine grain sizes. We believe that the finer grained schistose lujavrites may well owe their texture to a quenching process of this nature. Other arguments against this theory are that the naujaites, considered to be contemporaneous with the kakortokites show only a very weak layering (Sørensen, 1969); also it is difficult to visualise how, after a loss of gas pressure, the vent could become sealed and the pressure restored by crystallisation of only a few metres of rock, especially as it is rich in volatile-bearing phases.

Instead we tend to favour an origin by periodic convective overturns within the magma chamber as a result of cooling through the roof. The black layers were deposited during periods of strong flow when feldspars and nepheline were held in suspension, while the white layers formed during relatively tranquil periods. The red layers were probably also deposited during conditions of flow although eudialyte is normally equidimensional and does not show lamination except in a few cases such as layer +16 red which is strongly laminated. The arguments for this theory have been discussed by Upton (1961), but its opponents claim that the lamination could equally well be caused by compaction under gravity. We have found additional structures discussed below which also suggest that currents were operative, at least at times.

Wager & Deer (1939, p. 270) pointed out that conditions for convection are at an optimum when the mass of liquid has a diameter of about four times its thickness, a condition found in the Skaergaard intrusion, and Upton (1960, p. 118) considered that the layered rocks at Kûngnât (which contain abundent evidence for convection currents) were also deposited from a magma chamber which approached this form. In the present case it is not easy to estimate the size of the magma chamber owing to the Lakseelv fault, but it appears that it was not far removed from this optimum relationship. In combination with the apparent low viscosity of the magma (see Ferguson, 1964, p. 16) and the established operation of convection currents in other intrusions such as Skaergaard and Kûngnât, we believe it would be surprising if convection had not also operated in Ilímaussaq and our observations indicate that in fact it did.

Sørensen (1969) was opposed to the idea of convection currents on the grounds that there is evidence for vertical inhomogeneity within the magma chamber especially with regard to an upward concentration of volatiles. This argument cannot easily be dismissed and we must conclude that the origin of layering is still an open question.

INTRUSIONS CUTTING THE KAKORTOKITES

In addition to the syenite dykes and sills and the agpaitic pegmatite sheet already referred to, the kakortokites are cut by veins a few centimetres in thickness composed of felted aegirine and trending ENE-WSW, and albite-aegirine pegmatite dykes about 1 metre thick and trending ENE-WSW. In one of the latter dykes a pocket of well-crystallised natrolite was found containing an unidentified orange organic mineral of resinous appearance and amorphous to X-rays. Thin lamprophyre dykes containing olivine, lilac augite and large amounts of pleochroic brown amphibole also occur; they are 10 centimetres thick, trend NE-SW and are similar to other lamprophyres described from the district (Upton, 1965) which are believed to be very late. In any case they are the only rocks not obviously part of the Ilímaussaq intrusion observed to cut the kakortokites, this intrusion being late in the Gardar igneous cycle.

FAULTS CUTTING THE KAKORTOKITES

A swarm of small faults cutting particularly the western part of the area are clearly visible on the air photograph (fig. 1) trending almost due ENE-WSW. Wherever it was possible to determine the throw on these faults it was found to be small (i.e. only 1 metre or less). An example of such a fault which cuts some finely layered trough-banded kakortokite is shown in fig. 5.

The margin of the kakortokites against the green lujavrites along Lakseelv was assumed by Ferguson (1964) to be faulted and, although no large-scale faulting can be seen here owing to poor exposure, we support this view. On the southern side of Lakseelv the kakortokite dip is of the order of 20° as already mentioned, while on the northern side the layering dips around 70° possibly as a result of disturbance to an originally lower dip by the faulting. To the south of Lakseelv in its lower part the rocks are typical kakortokite of unit −4 while opposite on the northern side the rocks are poorly layered, contain acicular ferromagnesian minerals, are rather fine-grained and pass rapidly into green lujavrite. These latter rocks are tentatively correlated on mineralogical and textural grounds with the highest kakortokites found outcropping just below Laksefjeld. If this interpretation is true it suggests

Fig. 5. Minor fault cutting finely-layered, trough-banded kakortokite near marginal pegmatite on side of Kangerdluarssuk. A matchbox (3.5 × 5.2 cm) on the upper limb of the leucocratic layer gives the scale.

a throw for the fault in this region of ca. 350 m. (The throw estimated from the topographic height of the upper surface of the Julianehåb granite on opposite sides of the fjord gives a value of the order of 600 m. However, no confidence can be placed in this as it is clear that the basement possesses considerable relief at the present day and probably did so in Gardar times). As no faulting can be seen cutting the country rocks to the east of the intrusion and the rocks within the intrusion appear to be the same on each side of Laksedal in its upper part, it appears that the throw gradually increases in a westerly direction and dies out to the east.

THE MARGINAL PEGMATITE

The marginal pegmatite forms a boundary around the whole of the kakortokite against the marginal augite-syenite. It is approximately 50 m wide and so far as has been determined consists of the same minerals as the kakortokites but with much coarser development. Its boundary with the normal kakortokite is not sharp; veins finger into the finer-grained rocks over some distance, and the kakortokite layering tends to become indistinct on approaching the pegmatite. In some places the kakortokites show finer-scale layering close up to the margin (fig. 6 also fig. 5). The pegmatite is characterised by extreme heterogeneity and is difficult to sample representatively.

The origin of marginal pegmatites in the quartz syenites of Kûngnât has been discussed by Upton (1960) who suggests that they were caused by diffusion and concentration of volatiles in the cooler parts of the magma chamber. These pegmatites are reminiscent of pegmatitic patches observed by one of us (CKB) in the marginal border group of the Skaergaard intrusion, while the pegmatites developed around inclusions are similar texturally to those developed around gneiss inclusions in Skaergaard and figured by Wager & Brown (1968, p. 124).

OTHER STRUCTURES WITHIN THE KAKORTOKITES

Fine-scale layering, etc.

Fine-scale layering, structures resembling current bedding, and trough-banding have been noted in some places. These closely resemble similar features widely reported from layered intrusions by Wager & Brown (1968), including many from SW Greenland, as at Kûngnât (Upton, 1960) and Nunarssuit (Harry & Pulvertaft, 1963) and are taken as evidence for currents in the magma.

Examples of trough banding occur in the lowest exposed horizons in the western part of the kakortokites some 4 to 6 m from the border pegmatite (fig. 5). The troughs are bilaterally symmetrical and oriented with their long axes perpendicular to the intrusions margins, i.e. pointing inwards as do the Skaergaard examples. The largest trough-bands are as much as 14 m wide, but only 1 m or so deep, although examples narrower and with a much greater relative depth occur.

As described earlier, the large-scale layering found throughout, and so typical of the kakortokites, tends to die out within a few metres of the margin and be replaced by a much finer scale layering (fig. 6). It is in this type of rock that the trough bands occur, and consist of fine-scale, gravity-stratified layers. The most extreme crystal sorting occurs in the lower parts of the trough and becomes less distinct passing upwards. Their vertical extent is difficult to estimate as the topography is unfavourable. In some cases a distinct lineation of prismatic arfvedsonite, developed parallel to the axis of the trough (i.e. trending roughly NE and dipping 10°), may be seen in the field. In one example a single trough band becomes differentiated into two on passing upwards.

Poorly-developed trough banding and angular disconformities in the layering also occur on Kringlerne at a height of 330 m in unit +4, again close to the border pegmatite.

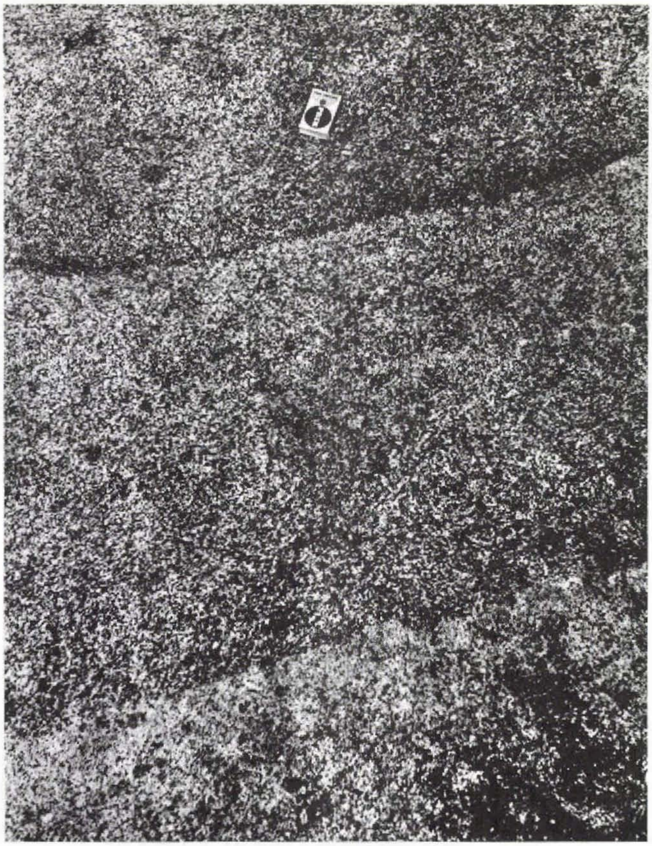

Fig. 6. Detail of fine-scale layering near marginal pegmatite.

Unit +4 contains numerous features apparently indicative of magmatic flow as mentioned earlier (fig. 4). These include minor disconformities in the layering and current bedding which are apparent because this unit contains a considerable amount of fine-scale layering. As this horizon lies just above the zone of large inclusions, and the most striking of these features occur near inclusions, it is believed that they have originated from currents initiated by the settling of these blocks.

The slumped zone

An area of dark fine-grained rocks, containing in places abundant clots of eudialyte, occurs along the fjord in its innermost part. This was mentioned by Ferguson (1967) but was not investigated in detail and its nature was not known prior to our own work. We now believe that these rocks represent a portion of the sequence which

Fig. 7. Part of the slumped kakortokites, south side of Kangerdluarssuk.

has undergone slumping at a time when the cumulus minerals were still unconsolidated. A general view of a portion of this zone is shown in fig. 7.

These rocks are found from the lower part of Lakseelv in a westerly direction to about 600 m east of the border pegmatite. Their upper part lies in layer −4 white such that in no place is −3 black involved. The thickness of the slumped rocks varies from about 10 cm in their westernmost exposure, and increases eastwards where the maximum thickness cannot be observed because the rocks dip below sea level. The lowest horizon to have been involved, so far as can be seen, is layer −6 white and at least 3 units have therefore been affected.

The slumped kakortokite is usually a medium-grained mesocratic rock showing distinct lamination. The feldspar and ferromagnesian minerals in this rock are up to 4 mm in size. Frequently it contains lenses or irregular bodies of a finer grained, more melanocratic rock lacking lamination and with 1-3 mm grains of eudialyte which frequently form clusters up to 0.5 cm in diameter. In the upper part of the slumped zone, there are coarse leucocratic lenses and veins rich in eudialyte and feldspar which lie parallel to the lamination of the host rock. Fig. 8 is a close-up picture of a typical rock in the lower part of the slumped horizon.

Depth of unconsolidated crystal mush

The maximum observable thickness of the slumped zone is about 16 m (that is from −6 white to −4 white). Layer −6 black strikes 62° and dips 22° NNW, and is completely unaffected by the slumping. Between this and the clearly slumped material the lamination has been strongly disturbed and irregular bodies and lenses of compact melanocratic material are found. It has occurred to us that this may represent pressed-out intercumulus liquid but we have little evidence to substantiate this. From this it seems that at least 18 m of material was unconsolidated at the time of slumping. Ferguson & Pulvertaft (1963, p. 16), from observations of the influence of the large inclusion on the underlying kakortokite layering exposed in the Kringlerne cliffs, estimate that the thickness of unconsolidated sediment was about 20 m. These estimates contrast strongly with estimates for layered basic bodies e.g. Rhum, estimated to be about 1.5 m (Brown, 1956) and Stillwater 3 m (Hess, 1960). Similarly the evidence from the larvikitic syenites of Kûngnât (Upton, 1960, p. 118) shows the depth of unconsolidated crystal mush to have been only about 1 m, although this is a minimum estimate based on the depth of erosion in trough-banded features. Thompson & Patrick (1968) interpreted the slumping structures in the Sarqâta qáqâ intrusion (Ubekendt Ejland) as indicative of an 8 m layer of unconsolidated mush which is the nearest estimate to those from Ilímaussaq known to us.

Fig. 8. Detail of slumped kakortokite.

Angle of rest of unconsolidated material

As stated above, the dip of the layering in the slumped zone of the kakortokites is 22° and this we believe is close to the original dip.

If we compare this maximum angle of rest with other estimates in the literature we find a value of 10-15° given by Brown (1956, p. 38) for the ultrabasic rocks of Rhum (which crystallised from a basic magma), although Wadsworth (1961, p. 41) found primary layering dipping at 35-40° (however this was rare and normally such layering was disturbed by slump-structures). In the Bushveld intrusion, Ferguson & Botha (1963, p. 269) found an angle of rest of about 40° and in the augite syenites of the Nunarssuit intrusion Harry & Pulvertaft (1963, p. 122) observed rhythmic layers which increased in dip until about 45° whereupon they showed signs of slumping. Similarly values of 40° to 50° were reported by Upton (1960, p. 116) for certain Kûngnât syenites although lower angles of dip (10-25°) were found in syenites of another unit of the intrusion and were suggested as being due to lower magma viscosity, the result of higher volatile content.

From this limited available information it seems that slumping occurred in the Ilímaussaq crystal mush at a rather low angle of rest as might be expected in an agpaitic magma with its very low viscosity (see Ussing, 1912, p. 361).

MEASUREMENTS OF Zr AND Nb CONTENTS

Instrumentation and calibration

Measurements were carried out in both the laboratory and the field using isotope-excited X-ray fluorescence for Nb and Zr, the two main elements of economic interest in the kakortokites, and it is planned to extend the work to further elements in future. The principles of this method have already been discussed by Clayton & Cameron (1966) and Wollenberg *et al.* (in preparation).

The experimental set-up used in the laboratory has a combined source/sample holder arranged as shown in fig. 9. The source is a 1 mCi ^{109}Cd sealed disc which emits 22 keV Ag X-rays and the detector (Xe-filled proportional counter with a Be window) is shielded against primary radiation by backing the source with Pt. Movable filters mounted between the source and detector window are made of Rb and Sr for the Zr determinations and Y and Sr for Nb. Experiments showed the sensitive sample area to be about 15 cm^2.

Detector pulses pass via a charge-sensitive pre-amplifier, a main amplifier and a single-channel analyser to a scaler/timer unit and printer. Our measurements were carried out with the analyser channel covering the approximate energy range 15 to

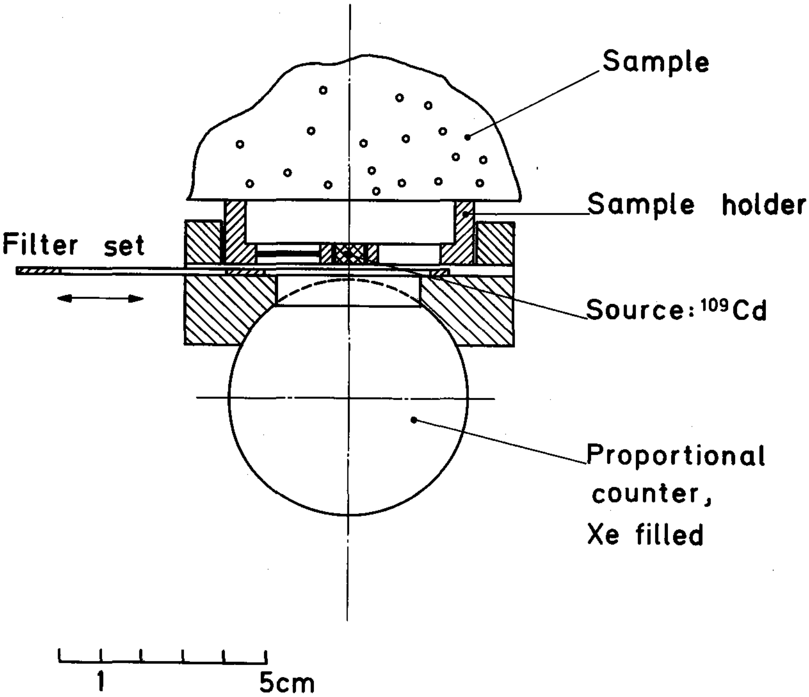

Fig. 9. Diagram showing layout of apparatus used for laboratory measurements of ZrO_2 and Nb_2O_5.

19 KeV, no adjustment being needed between Zr and Nb. Counting time was 200 sec.

Samples, collected as large specimens of several kilograms, were reduced to convenient hand specimen size by means of a diamond saw. This gave a reproduceable surface for measurement.

The instrument was calibrated using 26 kakortokite specimens selected to cover a wide range of values. After measurement, 15 cm^2 by 3 mm-thick discs were cut by the diamond saw, crushed and measured in a normal commercial X-ray fluorescence spectrograph. The results of this calibration are shown in figs. 10 and 11. The slopes of the straight line calibration curves calculated by regression analyses have relative standard deviations of 4% for ZrO_2 and 10% for Nb_2O_5, which are considered quite satisfactory for our purposes. The greater uncertainty for Nb is associated with its lower concentrations in the rocks. Detection limits of 0.6% for ZrO_2 and 0.2% for Nb_2O_5 were also calculated by regression analysis.

For field determinations we used a portable single-channel analyser (Lövborg, 1967) and a commercially available measuring head (Nuclear Enterprises Ltd.), incorporating a scintillation detector. Measurements were carried out directly on the rock surface, the fluorescent X-radiation being counted through each filter for 30 sec.

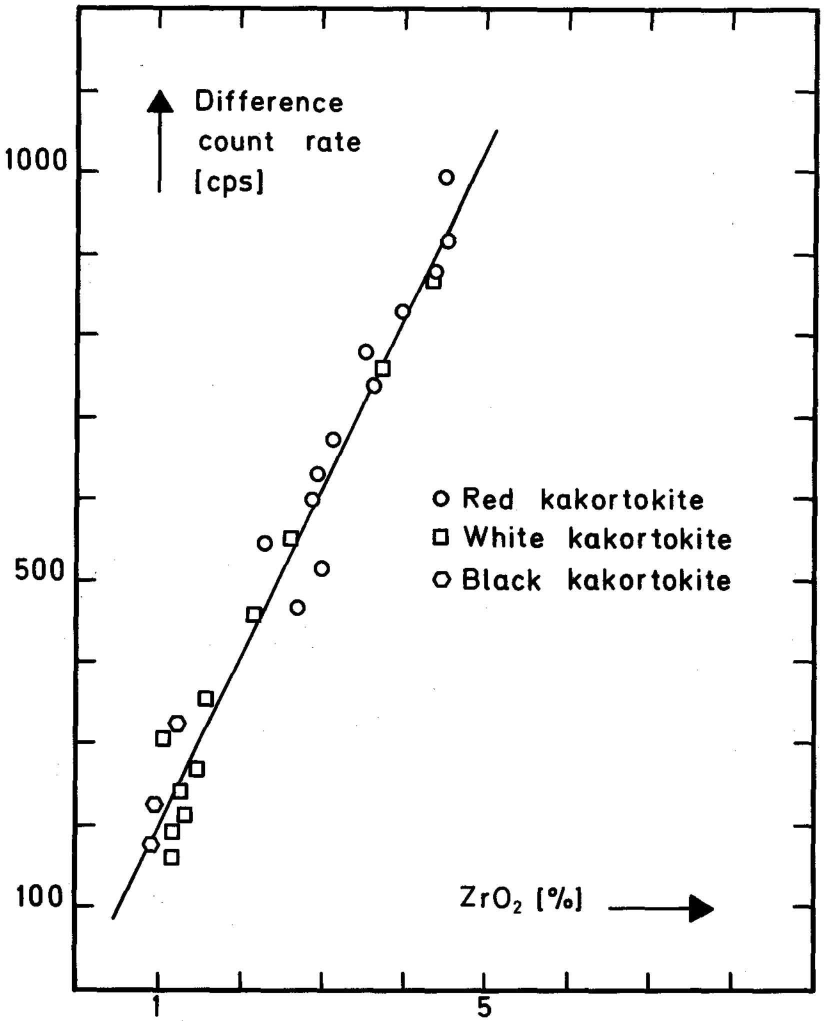

Fig. 10. Calibration curve for the laboratory measurements of ZrO_2. The values along the abcissa are derived from ordinary X-ray fluorescence analysis as described in the text.

Calibration of the field equipment was made regularly using 4 discs of eudialyte-bearing rock (collected by Kryolitselskabet Øresund A/S, see Allen & Charsley, 1968, p. 128) whose ZrO_2 and Nb_2O_5 contents are accurately known. A typical calibration curve is shown in fig. 12. A further control was made by making wet chemical analyses of hand specimens taken from unit 0. The results of this are shown in table 2 (along with TiO_2 contents which are necessary owing to interference between TiO_2 and Nb_2O_5) and are in reasonable agreement with values obtained by the field method on similar rocks.

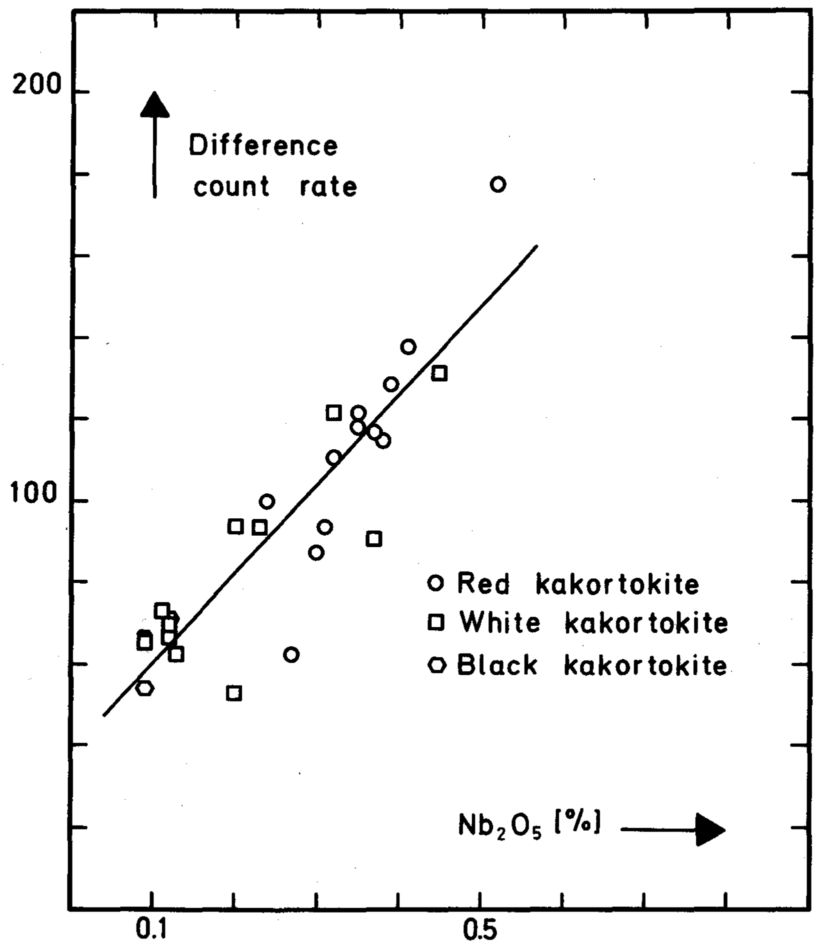

Fig. 11. Calibration curve for the laboratory measurements of Nb_2O_5. The values along the abcissa are derived from ordinary X-ray fluorescence analysis as described in the text.

Measurements using the field equipment are extremely rapid; several hundred may be made in a day. The loss of accuracy of standard laboratory methods is offset both by this speed and by the possibility of measuring in places which cannot readily be sampled. It is particularly valuable for investigating element variations across veins, layered features, etc. One disadvantage of the instrument as described is the time required for changing filters of sources in the measuring head, but improvement is possible in this respect.

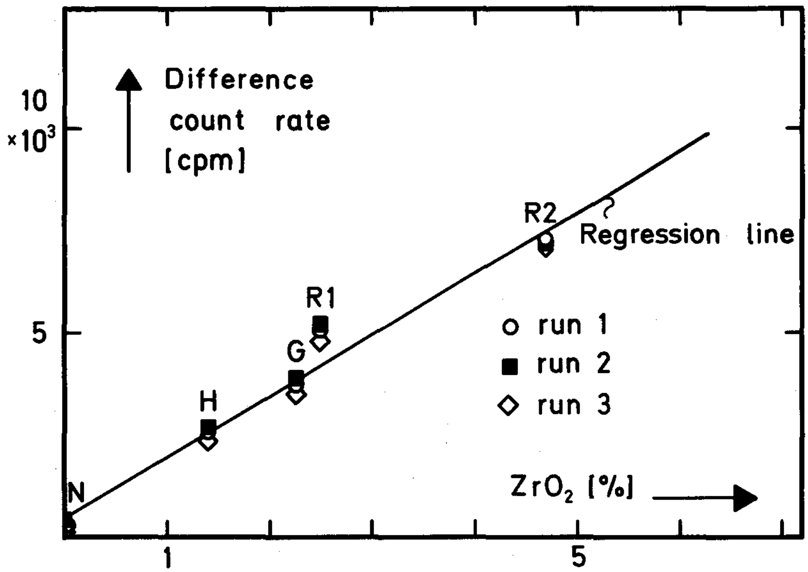

Fig. 12. Example of a calibration curve for the field equipment using standard kakortokite samples.

Table 2. Wet chemical analyses of typical specimens from unit 0

	ZrO_2%	Nb_2O_5% (corrected for Ti interference)	TiO_2%
0 black	1.14	0.05	1.22
0 red	7.09	0.56	0.36
0 white	1.09	0.10	0.36

Analyst: S. Aa. Markland (formerly Jensen).
Methods: ZrO_2 by cupferon, Nb_2O_5 by thiocyanate and TiO_2 by hydrogen peroxide.

Results of laboratory measurements

Laboratory measurements on 126 samples of red kakortokite, 74 white and 68 black have been made. The difference count rates (i.e. between counts made with the two filters for each element) have been converted to percentages using the calibration

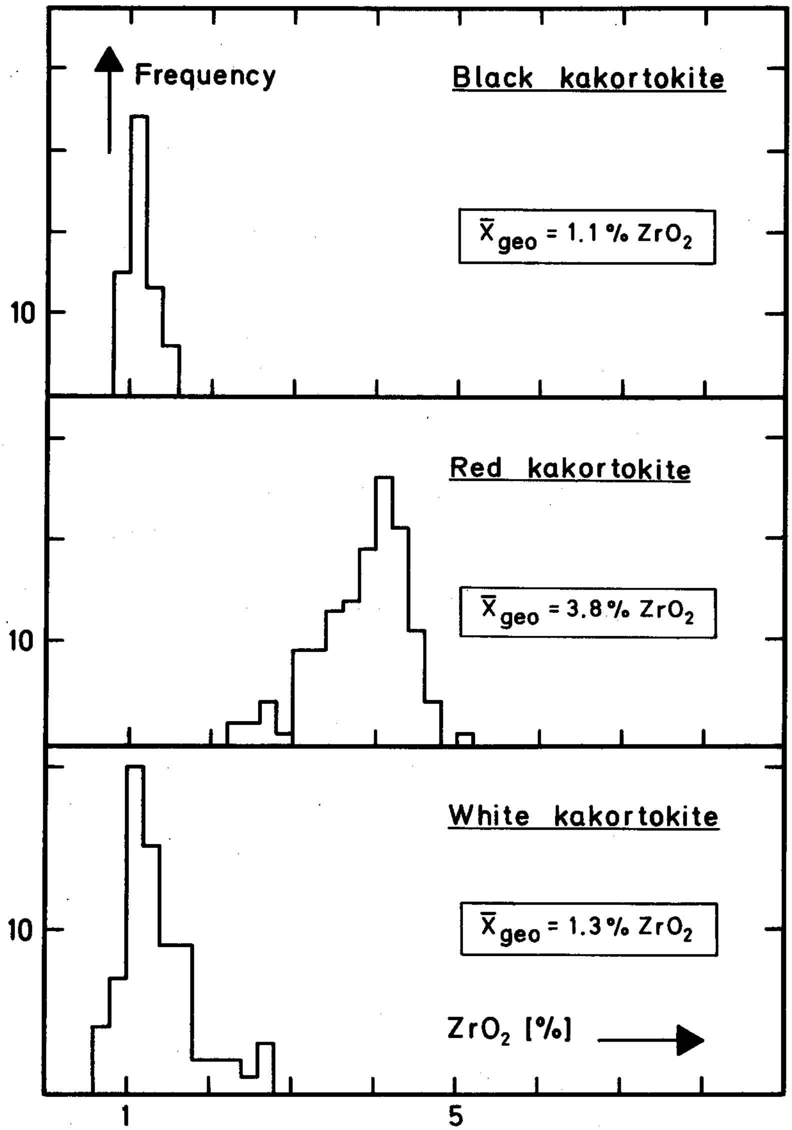

Fig. 13. Frequency distribution of ZrO_2 concentrations in the three kakortokite types from laboratory measurements.

curve referred to above and have been plotted on histograms (figs. 13 and 14), which give an estimate of the average ZrO_2 and Nb_2O_5 contents of the three kakortokite types. The skewness which appears on certain of these histograms is no doubt due to subjective factors in the division between the various types, as both transitions black to red and red to white kakortokite are in all cases gradual.

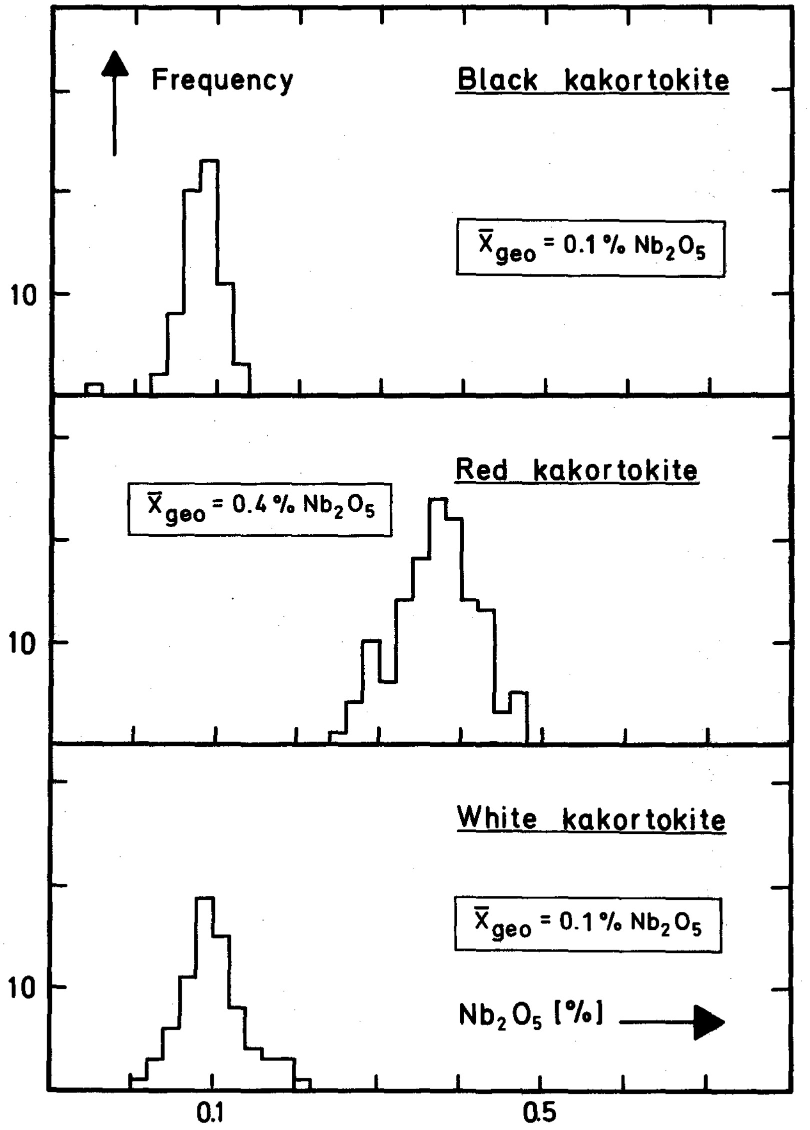

Fig. 14. Frequency distribution of Nb_2O_5 concentration in the three kakortokite types from laboratory measurements.

A correlation plot of ZrO_2 against Nb_2O_5 for the total of 268 determinations is shown in fig. 15. Although the spread is considerable there is clearly a significant linear correlation; ZrO_2/Nb_2O_5 ratios average 9.5 for red kakortokites, 9.8 for white and 10.7 for black with a ratio of 9.8 for all the kakortokites.

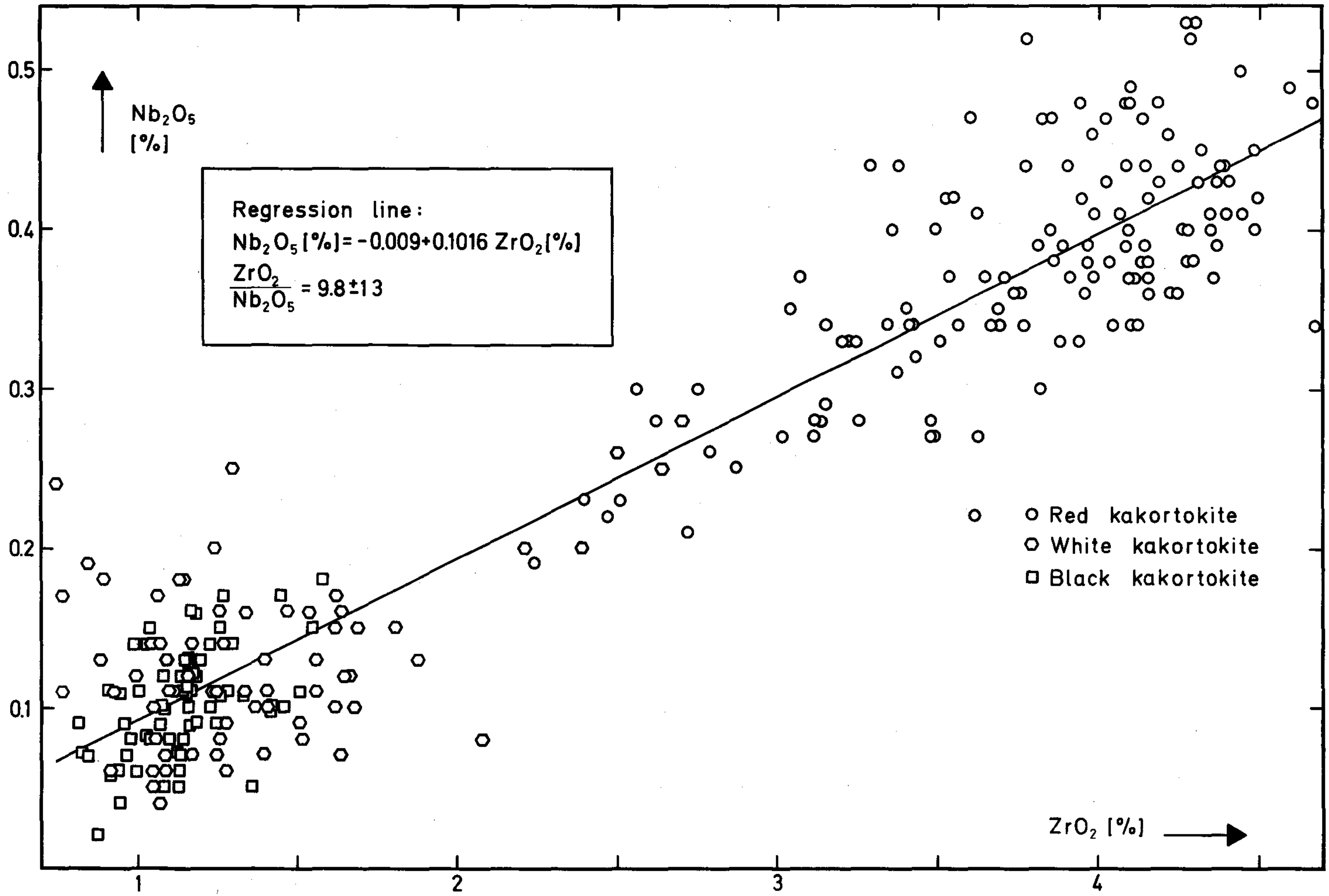

Fig. 15. Correlation plot of ZrO_2 against Nb_2O_5 for the data shown in figs. 12 and 13.

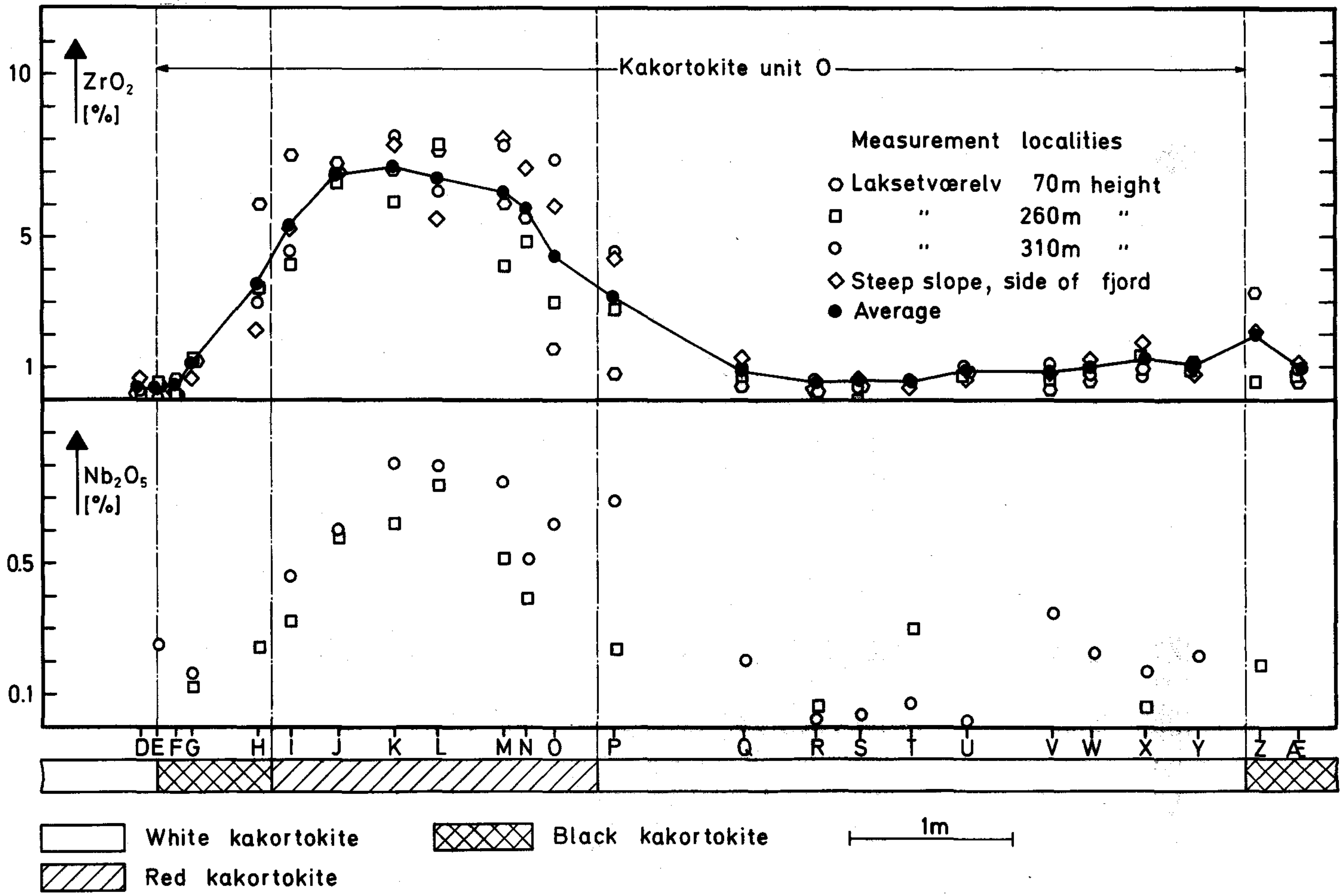

Fig. 16. Distributions of ZrO_2 and Nb_2O_5 with height within unit 0 at four widely separated localities.

Results of field measurements

In order to get an idea of the distribution of ZrO_2 and Nb_2O_5 both vertically and horizontally in a single layer we made detailed field measurements in unit 0 at four localities indicated in fig. 3. This unit was chosen because it is relatively easy to follow and recognise at different localities but it should be remembered that it is by no means a typical unit. The results are shown in fig. 16. In conjunction with this we made observations on the petrographical features visible on the natural outcrop surface at the various measuring points and these are given in table 3. In spite of the difficulties of correlating the measurements at the different widely-separated localities, it appears from this figure that ZrO_2 and Nb_2O_5 show very similar distribution patterns over the entire outcrop of unit 0.

We have also made a traverse across almost the entire exposed kakortokite sequence starting at 450 m above sea level in unit +16 and continuing downwards to unit −11 on the shore line. In spite of the difficulties caused by steep slopes and loose boulders this was done in less than three days with 6 to 9 measurements in each unit. The results of this traverse are shown graphically in fig. 17 and give a good picture

Table 3. Description of traverse measured for Zr and Nb in unit 0 at bottom of Laksetværelven

Station no.	Description
A, B and C	White layer of unit −1. Largely composed of 1 cm × 2.5 mm microcline showing marked lamination. Arfvedsonite and eudialyte minor in amount.
D	Boundary between unit −1 and unit 0. Very sharp over less than 0.5 cm.
E, F and G	Black layer of unit 0. G lies about 33 cm above D. Rock composed mainly of arfvedsonite. Feldspar smaller in amount and size than in layer −1 white.
H	Lies some 40 cm above G in the very diffuse boundary between layer 0 black and layer 0 red.
I, J	Typical red kakortokite with saccharoidal texture due to abundance of equidimensional eudialyte. J lies about 49 cm above H.
K, L	Appears visually to be the most eudialyte-rich part. L lies 62 cm above J.
M, N, O, P	Decreasing eudialyte content with P transitional to white kakortokite. Arfvedsonite poikilitically enclosing eudialyte and nepheline. P lies ca. 109 cm above L.
Q	White kakortokite. Microcline now coarser and similar to that in A, B and C described above. Eudialyte minor in amount, arfvedsonite still poikilitic. Lies 80 cm above P.
R-Y	White kakortokite very similar to A, B and C. Arfvedsonite no longer poikilitic. Y is 274 cm above Q.
Z	Y and Z which are separated by about 30 cm lie in the diffuse boundary zone between unit 0 and unit +1.
Æ	Black unit +1 differs from black unit 0 in having similar sized microcline to those in the white layers below and above, whereas in unit 0 they are distinctly smaller.

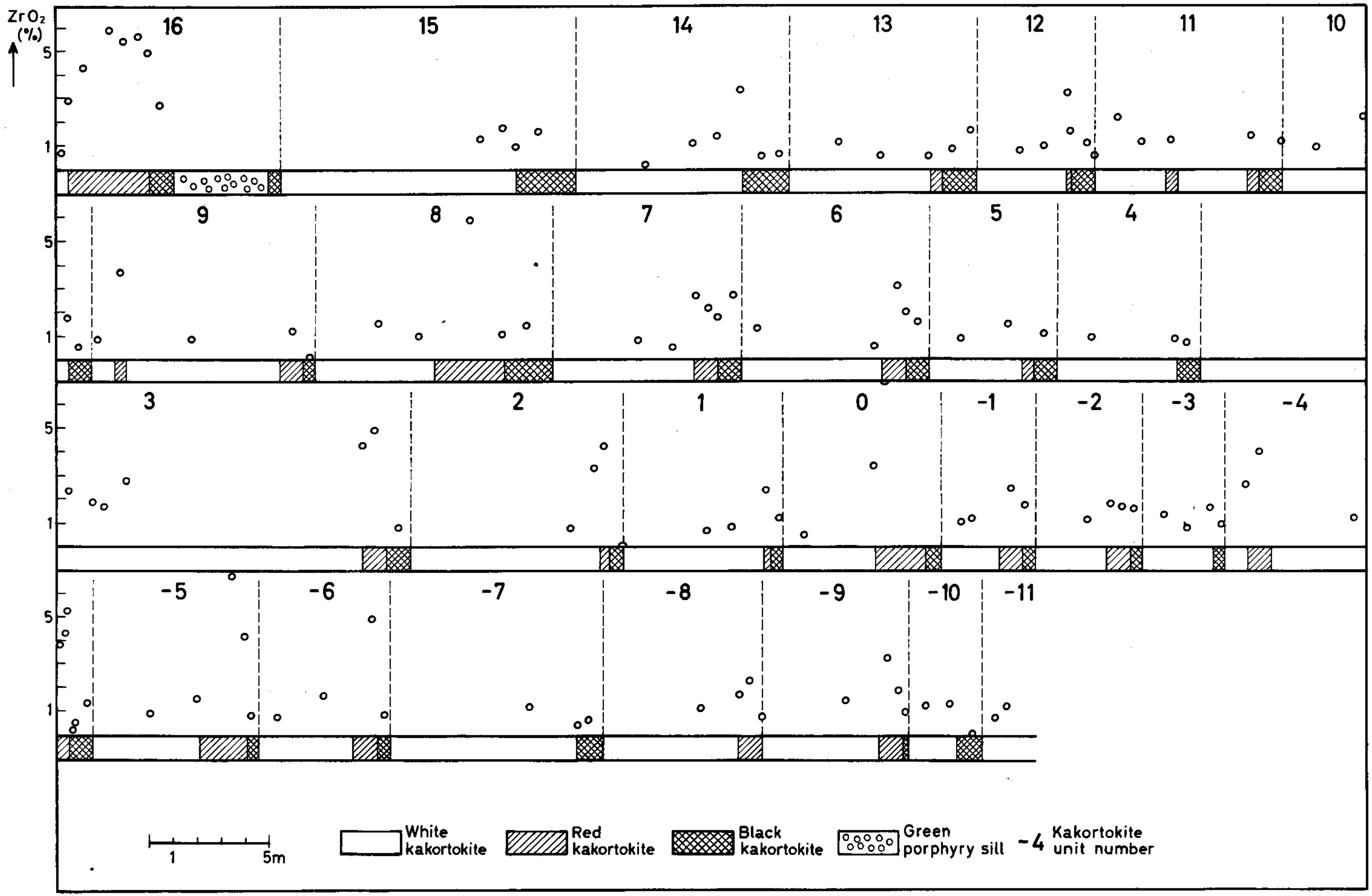

Fig. 17. Distribution of ZrO_2 with height within the entire exposed kakortokite sequence.

of the differences in ZrO_2 between the various units (fig. 17 should be compared with the description in table 1). Based on this information we have constructed a histogram. This is shown in fig. 18 and gives a mean (geometric) ZrO_2 content in the kakortokites of 1.2%, while if each measurement is weighted according to the thickness of the layer we get 1.4% ZrO_2.

We have also made measurements on the border pegmatite which is a possible economic source of Zr. As has earlier been pointed out sampling of this pegmatite is very difficult in view of its coarseness and inhomogeneity. Any sample would have to be extremely large to be representative; according to the criteria of Lafitte (1957, p. 101) several tons at least would be necessary. Field X-ray fluorescence measurements represent a convenient alternative to sampling because the mean and variability of a large number of measurements carried out fairly quickly can be rapidly assessed. We have made 140 ZrO_2 measurements, each spaced 0.5 m from the preceding one. These results are plotted in the histogram (fig. 19) which exhibits a marked skewness with a mean (geometric) of 2% ZrO_2 and a range of values exten-

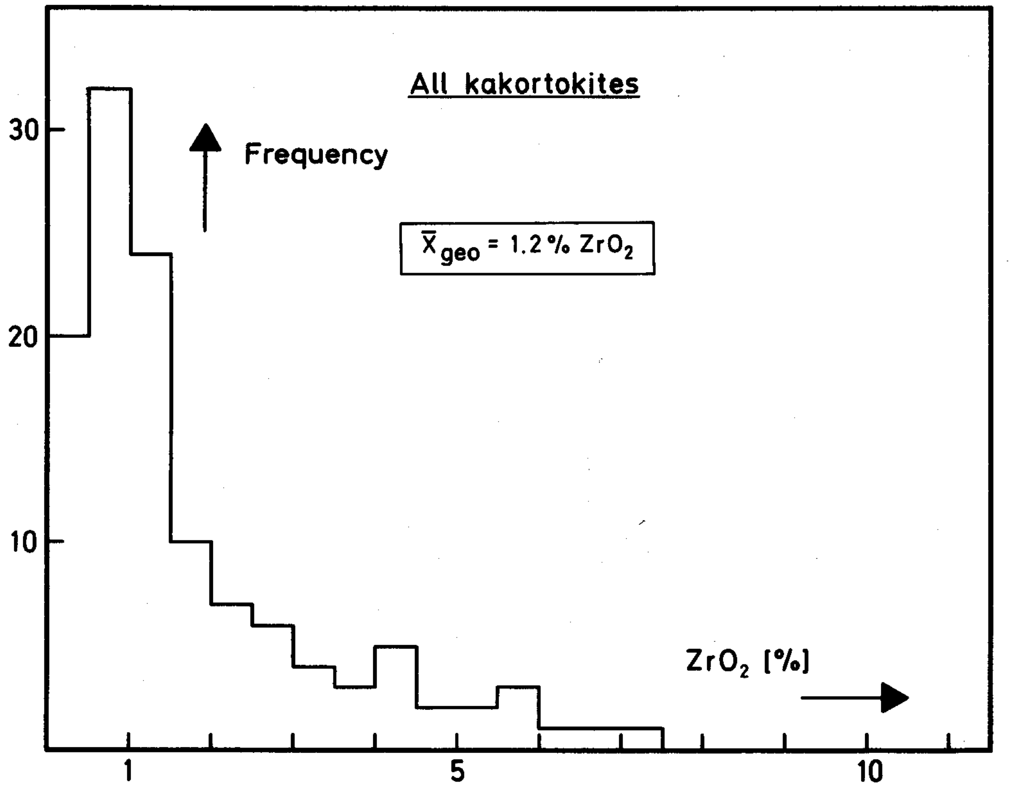

Fig. 18. Frequency distribution of ZrO_2 concentrations from the data given in fig. 16.

ding up to around 8%. Thus the border pegmatite is significantly higher in ZrO_2 than the average kakortokite.

An arithmetic mean of 19 measurements in the slumped layer along the side of the fjord gives a value of 1.2% ZrO_2, which is in good agreement with the idea that this slumped material represents several layers which have become homogenised in the slumping event.

Economic appraisal

As mentioned by Vlasov (1968, p. 312) and Jensen (1969) the eudialyte-bearing rocks constitute considerable resources of many rare elements such as Zr, Nb and rare earths. Furthermore they have the advantage over zircon sands (the present source of many of these metals) of being relatively easily processed – indeed the name eudialyte means "easily dissolved".

Although our investigations have not been directed towards prospecting or mining requirements, we are able to determine from our results the Zr and Nb resources of the kakortokites. Using a planimeter we have determined from the map the areas of kakortokite within each height interval delimited by the contours. Using the mean height between each contour we have calculated the individual volumes

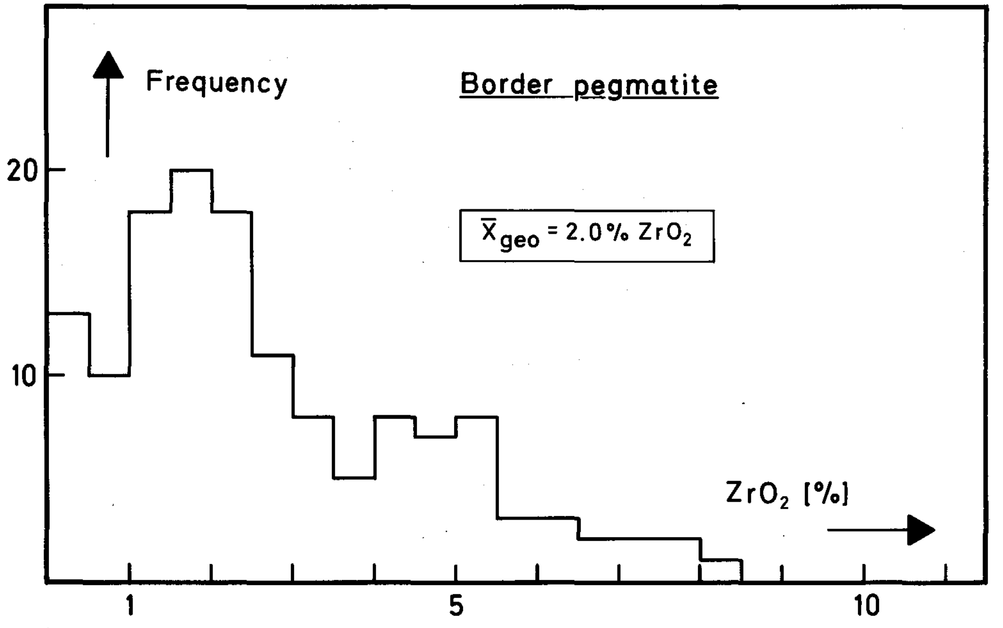

Fig. 19. Frequency distribution of ZrO_2 concentrations in the border pegmatite from field measurements.

above sea level corresponding to these areas west of Laksetværelven. The approximation involved in this calculation is believed to be only of the order of a few percent and is certainly comparable to the errors associated with our estimate of average ZrO_2 content. Using this volume and the mean specific gravity of kakortokite as given by Ferguson (1967) we have converted this to the total weight of kakortokite and hence with our previous estimate of the average ZrO_2 content to a weight of ZrO_2. The figure obtained by this procedure is 51.6×10^6 tons ZrO_2 which clearly represents considerable reserves.

In combination with the mean ZrO_2/Nb_2O_5 ratio reported above, namely 9.5, we are able also to give the quantitity of Nb_2O_5 in this volume of kakortokite. This is 5.4×10^6 tons.

As the kakortokites as a whole have a relatively low ore grade it would clearly be advantageous to delimit smaller areas of higher grade, providing these still contain adequate tonnages for economic working. We consider that the two most promising areas in this respect are unit +16 and the border pegmatite. As earlier described, unit +16 outcrops over considerable areas on the top of Kringlerne, higher horizons having been largely stripped away by erosion. The red layer of this unit is about 3.5 m thick and covers an area of 158×10^3 m^2 as measured by planimeter. Taking the average density of red kakortokite as 2.79 (Ferguson, 1967) and the mean content of ZrO_2 as 4% (estimated roughly from fig. 17) we find that this single layer contains some 52 000 tons ZrO_2 and 5500 tons Nb_2O_5.

No attempt has been made to calculate accurately the total amount of ZrO_2 in the border pegmatite as it is not clear to us how much it would be technically feasible to mine. However, the average ZrO_2 content reported above is significantly higher than that for the kakortokites as a whole and so might well prove to be a more attractive source of ore.

In addition to these factors already discussed, an important consideration with regard to possible economic exploitation of the deposit is its accessibility. In this respect it is fortunately situated. Kangerdluarssuk is known to be of adequate depth right up to its head to permit navigation by large vessels, and furthermore south-west Greenland has a relatively mild climate so that fjord ice is present for only a comparatively short time. On the other hand however, drift ice is commonly encountered during certain months of the year outside the fjord although it does not generally penetrate far up towards its head.

CONCLUSIONS

Our work which is reported here forms a basis for further laboratory work on the petrology and geochemistry of the Ilímaussaq kakortokites and also a basis for further economic assessment. We do not pretend that either part of this work forms a complete whole, and especially the estimate of ore reserves given in the last section is to be regarded with caution until further investigations have been carried out with this purpose specifically in mind. For this we would suggest more detailed topographic surveying of the main areas of interest, diamond drilling of the favoured localities and further X-ray fluorescence surveys. It must be appreciated that our measurements were made with a newly developed instrument and our main purpose was to assess its value. Our tests have shown it to be extremely useful for the present purpose and for this reason its capabilities are being extented to further elements such as the rare earths.

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MAP 1

Kartografi: Margareta Christoffersen.

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