GRØNLANDS GEOLOGISKE UNDERSØGELSE
RAPPORT Nr. 60

The Geological Survey of Greenland
Report No. 60

The uranium deposit at Kvanefjeld, the Ilímaussaq intrusion, South Greenland

Geology, reserves and beneficiation

by

Henning Sørensen, John Rose-Hansen, Bjarne Leth Nielsen, Leif Løvborg, Emil Sørensen and Torkild Lundgaard

Contribution to the mineralogy of Ilímaussaq no. 30

KØBENHAVN 1974

(The Geological Survey of Greenland)
Østervoldgade 10, DK-1350 Copenhagen K

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1 map in pocket

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Abstract

The uranium-thorium deposit is located in part of an alkaline intrusion consisting of peralkaline, agpaitic nepheline syenites. The radioactive minerals are steenstrupine, uranium-rich monazite, thorite and pigmentary material. The radio-element content varies from 100 to 3000 ppm U and 300 to 15000 ppm Th. Reasonably assured ore in the main area with a grade of 310 ppm is calculated to 5800 metric tons of uranium in 18.6 million metric tons of ore. Estimated additional reserves with a grade of 292 ppm U are 29.4 million tons of ore with 8700 tons of uranium and 3.5 million tons of ore with a grade of 350 ppm yielding 1200 tons of uranium. Estimates of amounts of thorium ore are 2.6 times those of uranium.

A method of recovery of the uranium based on sulphating roasting and subsequent leaching with water is described.

CONTENTS

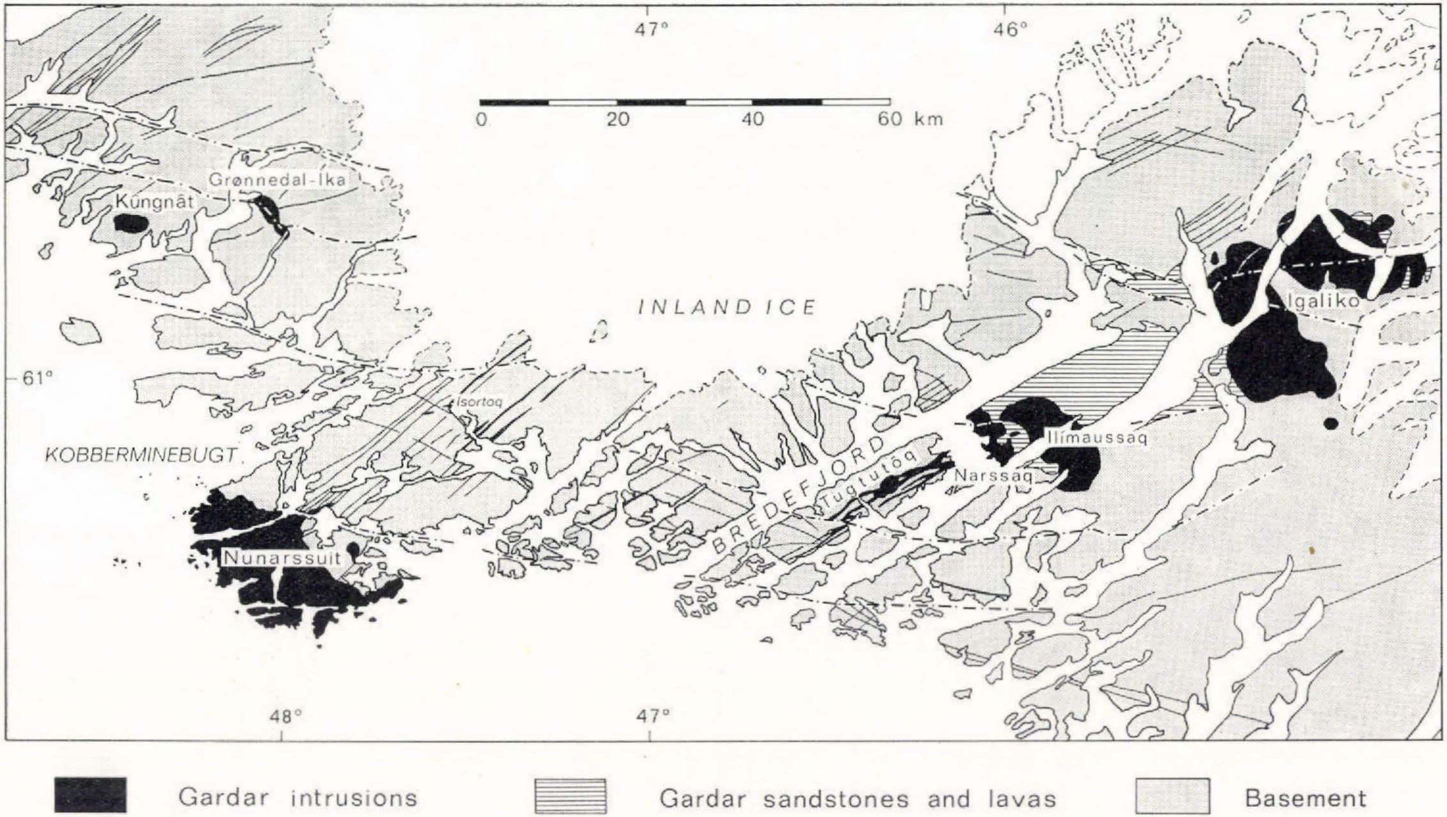


Fig. 1. Simplified geological map of the Gardar alkaline province (cf. Upton, 1974). The situation of the Ilímaussaq intrusion in South Greenland is indicated.

INTRODUCTION

The uranium-thorium deposit described in this report is located at Kvanefjeld in the north-western part of the Ilímaussaq alkaline intrusion, South Greenland (figs 1 and 2).

The deposit was discovered in 1956 during a systematic radiometrical reconnaissance survey of the whole intrusion (Bondam, 1959, 1960). A diamond drilling programme comprising 36 holes was carried out in 1958 during which a total length of drill core of 3728 m was obtained. The tonnage of uranium in ore containing more than 400 ppm U was estimated to be at least 4000 metric tons in the examined area.

Simultaneously with the field investigation, which at this stage was undertaken by the Geological Survey of Greenland (GGU), the Danish Atomic Energy Commission (AEK) and Kryolitselskabet Øresund A/S, the process of extraction of uranium from the ore was investigated in the chemical laboratories of the Danish Atomic Energy Commision. In 1962 200 tons of ore were quarried for this project.

In 1964 the Institute of Petrology of the University of Copenhagen was entrusted with the continued geological examination of the deposit, a program which was carried out for the Geological Survey of Greenland in close collaboration with the Danish Atomic Energy Commission Research Establishment at Risø.

A detailed topographical and geological mapping of the Kvanefjeld plateau was carried out in the years 1964—1968 and the preliminary map was published in 1969 (Sørensen, Hansen & Bondesen, 1969).

A new drilling programme was carried out in 1969 giving an additional core length of 1621 m from 7 holes.

The present report is based on the above-mentioned geological field work, on detailed radiometrical surveying of the plateau by means of geiger counters and gamma-spectrometric methods, on examination of the drill cores including a gamma-spectrometric scanning of the cores (Løvborg *et al.,* 1972), on numerous chemical analyses, and on petrological and mineralogical studies. The ore reserve is estimated and the report also contains an account of the laboratory investigation of the process of extracting uranium from the ore.

A detailed account of all stages of the geological work is presented in an internal GGU report (Sørensen, Rose-Hansen & Nielsen, 1971).

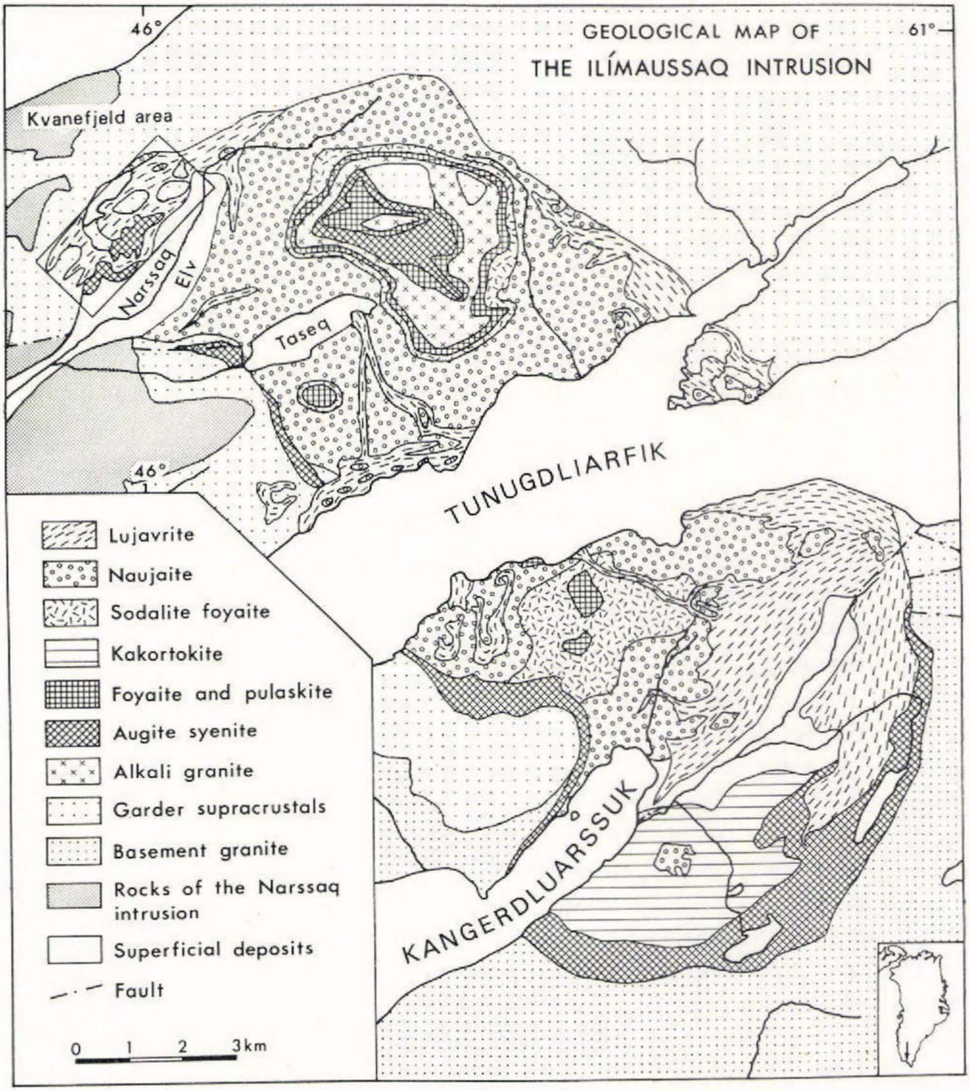


Fig. 2. Simplified geological map of the Ilímaussaq area, South Greenland based on Ferguson (1964) and Stewart (1964) with minor corrections.

LOCATION AND CLIMATIC CONDITIONS

The Kvanefjeld area is a hilly plateau between 500 and 685 m high, the mountain Kvanefjeld in the eastern part of the area being the highest point. The area

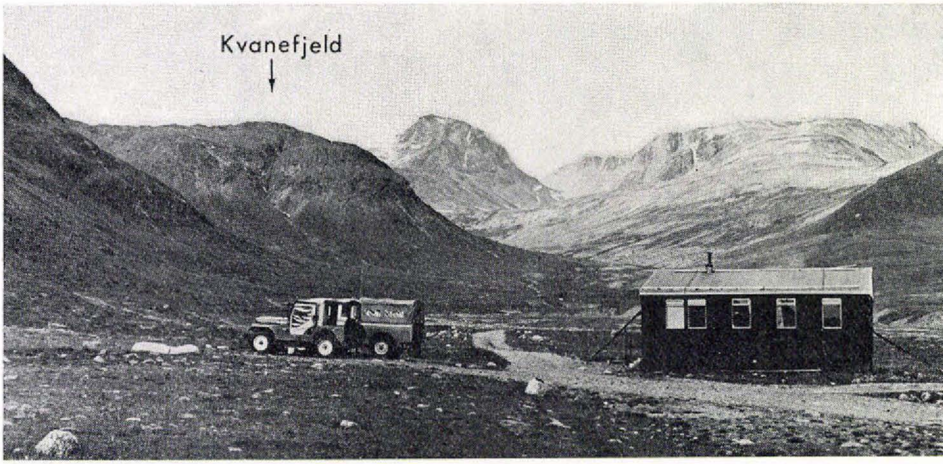


Fig. 3. The Kvanefjeld plateau (dark low mountain in the left background) seen from the geological base camp at Dyrnæs. The highest mountain is the Ilímaussaq mountain.

measures 2.5 km² and is made up of NE-SW rocky ridges separated by lower ground covered by glacial deposits, by lakes, and by vegetation.

The area is situated to the north of the river Narssaq Elv about 8 km to the north-north-east of the town of Narssaq. The geographical position is 60° 58' north, 46° 00' west.

The Kvanefjeld area is reached through the Narssaq Elv valley, which is about 1 km wide, by means of a mountain road starting at Dyrnæs (fig. 3) on the coast north of Narssaq and ending at an altitude of 300 m at the foot of the steep slope which forms the southern limit of the Kvanefjeld area (fig. 4). Admission to the plateau now takes place by a footpath but a road could be constructed to the north-east corner of the plateau. During the drilling programme an aerial rope-way was in operation.

The fjord and the natural harbour at Panernaq north of Narssaq (fig. 1) is normally navigable during most of the year, but may be temporarily closed by winter ice in midwinter and by icebergs in the summer.

The yearly average temperature is 1.5° C at Narssaq. The average temperatures in January and July are respectively – 3.3° C and + 7.5° C. The temperature at Kvanefjeld is about 3° C lower than these values due to its elevation. The yearly precipitation varies from about 1000 mm to about 3500 mm. In the period from October to April the major part of the precipitation is snow corresponding to a total of about 400 mm water. Most years the plateau is free from snow from late June to early September (L. B. Larsen, 1972, 1973).

The plateau is often veiled by clouds. There are most years many strong storms, partly in the form of föhn storms from the east or south-east.

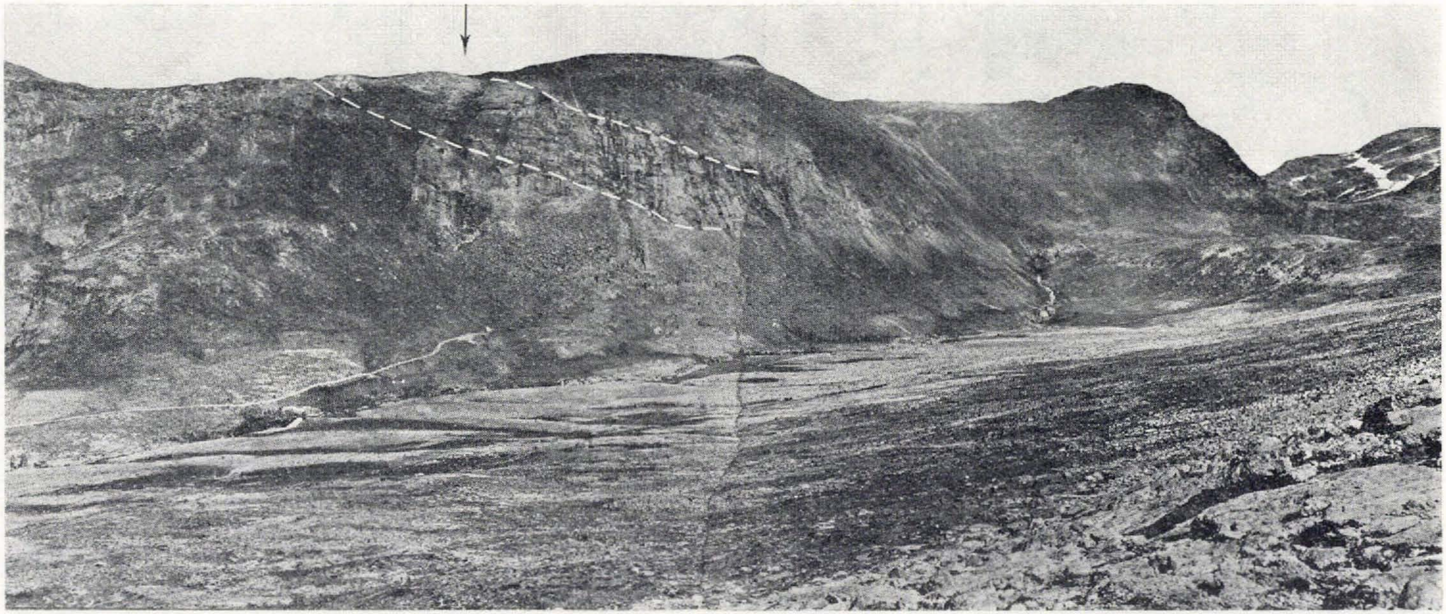


Fig. 4. Kvanefjeld seen from the south. The road in the river valley ends at an altitude of about 300 m. The lower part of the slope is mainly made up of naujaite, the upper part of syenite and fine-grained lujavrite. The 'blanket' of medium – to coarse-grained lujavrite and its accompanying uranium mineralization is marked with two dotted lines. The arrow indicates the entrance of the 'mine' from which 200 tons of ore were mined in 1962.

GEOLOGY OF THE KVANEFJELD AREA

The Kvanefjeld area is situated in the north-western part of the Ilímaussaq intrusion. The intrusion, which is 1020 ± 24 m.y. old (Bridgwater, 1965) forms part of the Gardar magmatic province of south Greenland (fig. 1). The province is made up of rocks of the gabbroic-alkaline association (Sørensen, 1965). The intrusion has been described by Ussing (1912), Sørensen (1958) and Ferguson (1964, 1971). The geology of the country rocks is described by Allaart (1973), Poulsen (1964), Stewart (1964) and J. G. Larsen (1973).

The Ilímaussaq intrusion, which covers about 150 km², is composed of an early augite syenite followed by strongly peralkaline, agpaitic syenites such as naujaites (poikilitic sodalite syenite), foyaites, kakortokites and lujavrites (table 1). The lujavrites were accompanied by hydrothermal veins. In the roof zone there are two small masses of alkali granite (table 1 and fig. 2).

Crystallization of the agpaitic magma took place under a roof of lavas and sandstone which prevented the escape of volatiles from the magma.

A general description of the geology of the Kvanefjeld area and a geological map is found in Sørensen *et al.* (1969), see also plate 1.

The Kvanefjeld plateau is situated at the north-western contact of the Ilímaussaq intrusion and is to the west, north and east bounded by the volcanic rocks of the roof of the intrusion. The volcanic rocks consisting of lavas, dykes, sills and minor sandstone dip gently towards the intrusion. The plateau is bounded to the south by a steep slope towards the Narssaq Elv valley. The slope is dominated by augite syenite and lujavrite at the top and by naujaite at the bottom. The major rock types found in the intrusion are listed in table 1.

The surface of the plateau is made up of a complicated lujavritic intrusion breccia. In the westernmost part of the plateau there are large and small blocks of syenite, alkali syenite, anorthosite and naujaite; in the easternmost part of the plateau the blocks consist of naujaite, foyaite and volcanic rocks. The blocks are enclosed in and intruded by several types of lujavrite.

The emplacement of the lujavrites is partly determined by NE-SW fracture zones, partly by the boundary between the roof of volcanic rocks and the underlying naujaite and syenite.

In the southernmost central part of the plateau an arching of the volcanic roof is underlain by sheet-like intrusions of medium- to coarse-grained lujavrite cutting all other rocks of the area, including the fine-grained lujavrites. This coarser grained lujavrite is accompanied by pegmatites and veins rich in analcime, pyrochlore, chkalovite and a number of other minerals (see for instance Sørensen, Danø & Petersen, 1971). The adjacent rocks are generally enriched in uranium

Table 1. The major rock types of the Ilímaussaq intrusion

rock type	texture grain size	essential minerals	minerals of interest	U ppm	Th ppm	Th/U
augite syenite	massive, layered, medium to coarse	alkali feldspar, titanaugite		3 (2–4)	8 (5–11)	2.7
sodalite foyaite	massive, coarse	alkali feldspar, nepheline, sodalite, aegirine-augite, arfvedsonite	eudialyte	16 (13–19)	48 (45–53)	3.0
naujaite	poikilitic, coarse	sodalite, alkali feldspar, aegirine, arfvedsonite	eudialyte, rinkite, villiaumite	12 (6–27)	26 (9–35)	2.5
kakortokite	laminated, layered, medium	alkali feldspar, nepheline, arfvedsonite	eudialyte, rinkite	18 (6–29)	45 (9–57)	2.5
lujavrite	laminated, fine	microcline, albite, nepheline, arfvedsonite, aegirine	eudialyte, monazite, lovozerite, steenstrupine, sphalerite, Li-mica, villiaumite	146 (117–1200)	154 (63–5500)	1
lujavrite (m-c)	massive, layered, medium to coarse	microcline, albite, nepheline, arfvedsonite, aegirine	steenstrupine, monazite	400 (50–1550)	890 (200–1100)	2.2

Based on Bondam & Sørensen (1958), H. Sørensen (1962, 1970 a), Løvborg *et al.* (1968 a, 1971), Gerasimovsky (1969), P. Sørensen (1971), Sass *et al.* (1972).

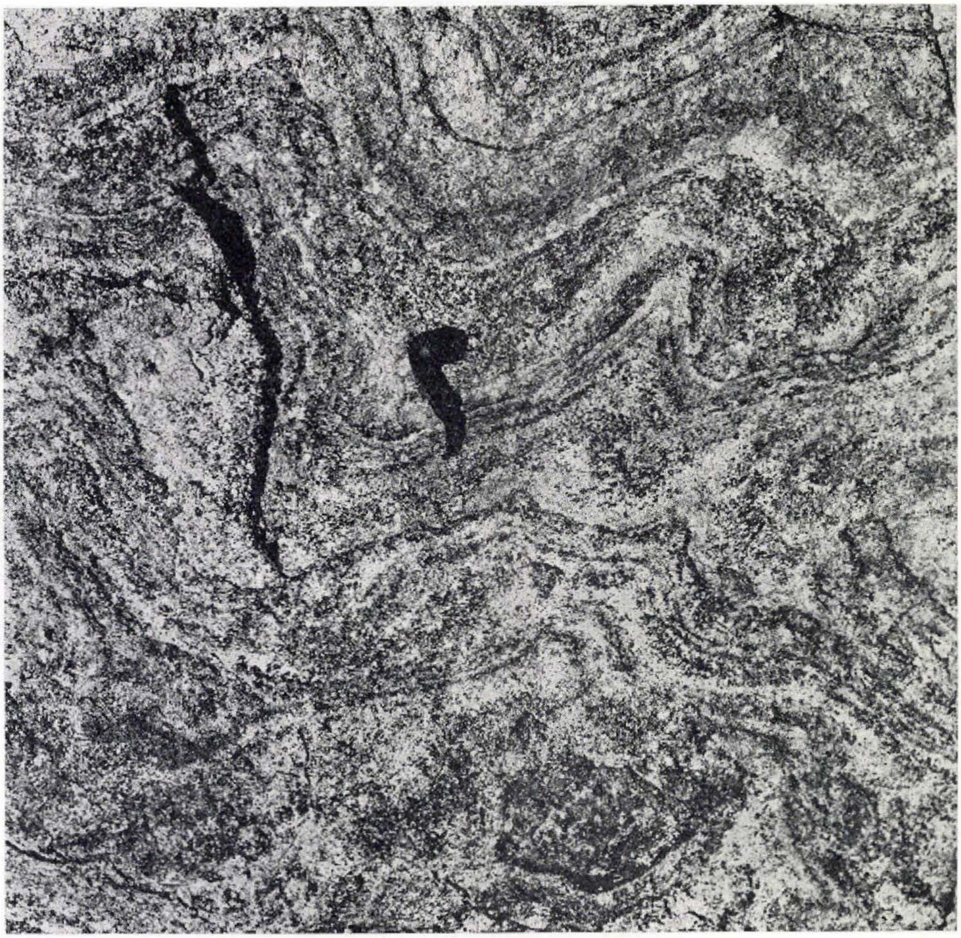


Fig. 5. Strongly folded and metasomatically altered complex of volcanic rocks and fine-grained lujavrite adjacent to body of medium- to coarse-grained lujavrite.

and thorium. Medium- to coarse-grained lujavrite also occurs in the lujavrite area around drill holes nos. 39–40 in the northernmost part of the plateau. The altered and recrystallized volcanic rocks and their veins of fine-grained lujavrite are strongly deformed and even folded adjacent to the medium- to coarse-grained lujavrites (fig. 5 and cf. Sørensen, Hansen & Bondesen, 1969).

A similar rock assemblage is found in the steep slope below Steenstrups Fjeld to the north-east of the plateau, also here with occurrences of radioactive minerals.

For further information on the geology, including the structural geology of the plateau, reference is made to Sørensen, Hansen & Bondesen (1969).

Table 2. The radioactive minerals and other minerals of economic interest in the Ilímaussaq intrusion

	ppm		weight percent						
	U	Th	Nb_2O_5	Ta_2O_5	ZrO_2	La_2O_3	CeO_2	BeO	Ref.
Steenstrupine (see table 3)* $Na_2Ce\ (Mn, Nb, Fe)H_2\ ((Si, P)O_4)_3$	2000–15000	2000–74000	0.2–4.4	0.04		15–30†			1, 2, 3, 4
Monazite $(La, Ce)PO_4$	138–12800	300–57300				36	43		1, 4, 5, 6
Thorite $(Th, U)SiO_4$	31000	405000							2, 4
Britholite $(Na, Ca, Ca)_5\ F(SiO_4, PO_4)_3$		6900							4
Eudialyte $(Na, Ca, Ce)_6\ Zr(OH, Cl)\ (Si_3O_9)_2$	50–600	30–340	0.6–1.0	0.06	14	0.5–1.6	1–3.4		1, 4, 5, 7, 8
Epistolite $Na\ (Nb, Ti)\ (OH)SiO_4$			32–37	0.2–0.5					4, 8
Lomonosovite $Na_2Mn, Ti_3(SiO_4)_4\ 2Na_3PO_4$									
Lueshite (igdloite) $NaNbO_3$			58–63						4, 8
Murmanite $Na(Ti, Nb)\ (OH)SiO_4$			0.5–10	0.01–0.1					4, 8
Pyrochlore $(Ca, Na)_2\ (Nb, Ta)_2\ O_6\ (O, OH, F)$	2000	7000	40–61	0.1–3.6					8, 9
Rinkite $(Ca, Na, Ce)_{12}\ (Ti, Zr)_2Si_7O_{31}H_6F_4$	3000–12000		2.4		0–6.5	4.5	9.3		3, 4, 8
Chkalovite $Na_2\ Be\ Si_2O_6$								11–13	4, 8, 11
Sorensenite $Na_4Sn\ Be_2Si_6O_{16}\ (OH)_4$								7–8	4, 12
Tugtupite $Na_8Be_2Al_2Si_8O_{24}\ (Cl, S)_2$								5	4, 10, 11
Villiaumite NaF									4, 14

* including hydrosteenstrupine
† expressed as $(Ce, La)_2O_3$

1. Sørensen (1962)
2. Wollenberg (1971)
3. Bøggild (1953)
4. Semenov (1969)
5. Gerasimovsky (1969)
6. New data
7. Hamilton (1964)
8. Hansen (1968)
9. Semenov *et al.* (1968)
10. Sørensen (1960)
11. Engell *et al.* (1971)
12. Semenov *et al.* (1965)
13. Sørensen *et al.* (1971)
14. Bondam & Ferguson (1962)

THE RADIOACTIVE MINERALS

The radioactive minerals known from the Kvanefjeld plateau are listed in table 2.

Steenstrupine is the most widespread uranium mineral (see Buchwald & Sørensen, 1961; Sørensen, 1962; Wollenberg, 1971). This mineral occurs as small interstitial crystals in fine-grained as well as in medium- to coarse-grained lujavrite (m-c lujavrite) indicating a primary origin. It occurs also as late poikilitic grains of irregular shape and apparently of late origin in both rocks. These grains are generally associated with analcime. Steenstrupine also occurs in veins of analcime in the m-c lujavrite, fine-grained lujavrite and altered volcanic rocks, and it forms crystals in a network of thin white veins of analcime-natrolite around the bodies of m-c lujavrite.

In the m-c lujavrite and the altered volcanic rocks there are pseudomorphs after an unknown mineral, which may perhaps have been steenstrupine. These pseudomorphs are composed of steenstrupine, monazite, thorite, aegirine, pectolite, analcime, etc. (Buchwald & Sørensen, 1961). They occur in analcime-rich rocks.

The Th/U ratio of steenstrupine varies from 1 to 7 with an average value of *c.* 3. Chemical analyses of steenstrupine are listed in table 3.

Monazite occurs as aggregates of small crystals (cf. Danø & Sørensen, 1959; Buchwald & Sørensen, 1961). The monazite of Ilímaussaq, according to autoradiographic analyses, is commonly only weakly radioactive; one sample chemically analysed has given 138 ppm U and 585 ppm Th (Sørensen, 1962). The monazite of the Kvanefjeld region is more strongly radioactive. Monazite from an analcime-pyrochlore-monazite vein has been chemically analysed by Asmund (1971) who found 1.28 % U and 5.73 %Th, Th/U 4.5. Wollenberg (1971) found by means of fission track measurements that monazite from a similar rock contains 0.5 % U, 24.6 % Th, Th/U 46. Both samples may contain thorite and steenstrupine as impurities. Monazite from two analcime-monazite bodies in the eastern part of the mine area has given 0.98 % U, 4.86 % Th and 1.50 % U, 7.4 % Th, Th/U 4.9.

Samples of monazite from m-c lujavrite and fine-grained lujavrite have given contents of 0.19 % U, 1.2 % Th, Th/U 9.7 and 0.2 % U, 2.3 % Th, Th/U 11.7, respectively (Wollenberg, 1971).

Thorite occurs as small grains which are yellow and isotropic in thin section. They are associated with steenstrupine and monazite. The identity of the mineral has not been definitely verified, but fission track analysis gives 2–3 % U and 28–53 % Th which supports the identification.

Pigmentary material is in places strongly enriched in uranium. It is associated with altered steenstrupine and also occurs as crusts on arfvedsonite. Fission track analysis gives contents of up to 2.5 % U and no or little Th (Wollenberg, 1971).

Eudialyte, britholite and *lovozerite* are weakly radioactive (Buchwald & Sørensen, 1961).

Table 3. Chemical analyses of steenstrupine and hydrosteenstrupine

	STEENSTUPINE			HYDROSTEENSTRUPINE	
	Tugtup agtakôrfia Bøggild 1953	Igdlúnguaq Semenov 1969	Taseq Asmund 1971	Kangerdluarssuk Bøggild 1953	Tuperssuatsiait Semenov 1969
SiO_2	26.72	29.78	27.4	20.61	21.50
TiO_2	*	0.34	0.78		0.37
ZrO_2					
ThO_2	2.13	2.42	3.98	3.84	3.86
$(Nb, Ta)_2O_5$	4.37	0.13‡	0.16	1.58	*
CeO_2	*			17.85	
$(Ce, La)_2O_3$	29.60	28.73†	26.5	15.52	33.13†
Y_2O_3	0.36			2.19	
Al_2O_3	–	1.77	6.23	0.40	1.70
Fe_2O_3	2.67	3.28	4.57	5.18	6.20
FeO	*	1.52			
Mn_2O_3	*			5.79	
MnO	6.60	3.86	2.71		3.85
MgO	0.31	0.09	0.05		1.64
BeO	*			1.22	
CaO	2.33	2.47	2.16	4.22	4.89
Na_2O	11.23	8.25	10.22	2.53	0.59
K_2O	*	1.19	0.82	*	0.52
Li_2O	*		0.065		
H_2O	3.45	4.31	8.07	12.73	13.08
F	1.24	1.32			3.70
P_2O_5	8.19	10.47	9.5	4.53	6.20
PbO				1.02	
B_2O_3			0.73		
U_3O_8		0.39			
	99.20	100.32	103.95	99.21	101.23
$-O = F_2$	0.52	0.55			1.55
	98.68	99.77	103.95	99.21	99.68

‡ $Ta_2O_5 = 0.04$ † see below * not detected

The composition of the lanthanides in steenstrupine

	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tu	Yb	Lu
Igdlúnguaq	31	50	4.1	12	1	0.1	0.5	0.1	0.5	0.1	0.6	0.1	0.6	0.1
Tuperssuatsiait	24	45	4.7	25	0.7	–	0.4	–	–	–	–	–	–	–

ON THE OCCURRENCE OF URANIUM ON THE KVANEFJELD PLATEAU

The occurrence of uranium and thorium in the Ilímaussaq intrusion is discussed by Bondam & Sørensen (1959), Buchwald & Sørensen (1961), Sørensen (1962, 1970 a) and Wollenberg (1971).

In this paper the following types of occurrences will be treated (plate 1):

1. The uranium mineralization associated with the medium- to coarse-grained lujavrites in the southernmost central part of the plateau (the mine area).
2. The uranium mineralization associated with the medium- to coarse-grained lujavrites in the northernmost part of the plateau.
3. Uranium and thorium in deformed and recrystallized rocks in narrow zones in the north-eastern part of the plateau.
4. The fine-grained lujavrites.

The uranium mineralization in the southernmost central part of the plateau (the mine area)

The most detailed exploration work has been carried out in the southernmost part of the plateau which contains the most promising uranium mineralization found so far in the whole region.

The uranium mineralization is mainly located in the contact zones between sheet-like masses of medium- to coarse-grained lujavrite and the roof cover of volcanic rocks intruded by fine-grained lujavrites.

The occurrence is conveniently divided into a south-western part, in which the mineralized rocks form the surface, and a north-eastern part, in which the mineralized rocks are concealed by the volcanic roof rocks. This concealed part is intersected by drill holes nos. 1, 2, 6, 8, 9, 10, 16, 17, 21 and 31 (figs 7, 8 & 10 and plate 1).

The south-western part is traced toward the west-north-west in drill holes nos. 19, 24 and 33 but only as thin sheets.

The uranium mineralized complex appears to be limited towards the north-east by a line marked by drill holes nos. 5, 4, 14 and 12.

The medium- to coarse-grained lujavrite outlined by surface exposure and drill holes is found over an area of 200 000 m^2 with a probable north-eastern extension of about 60 000 m^2.

On the occurrence of medium- to coarse-grained lujavrite

The south-western mineralized area is characterized by a rolling topography

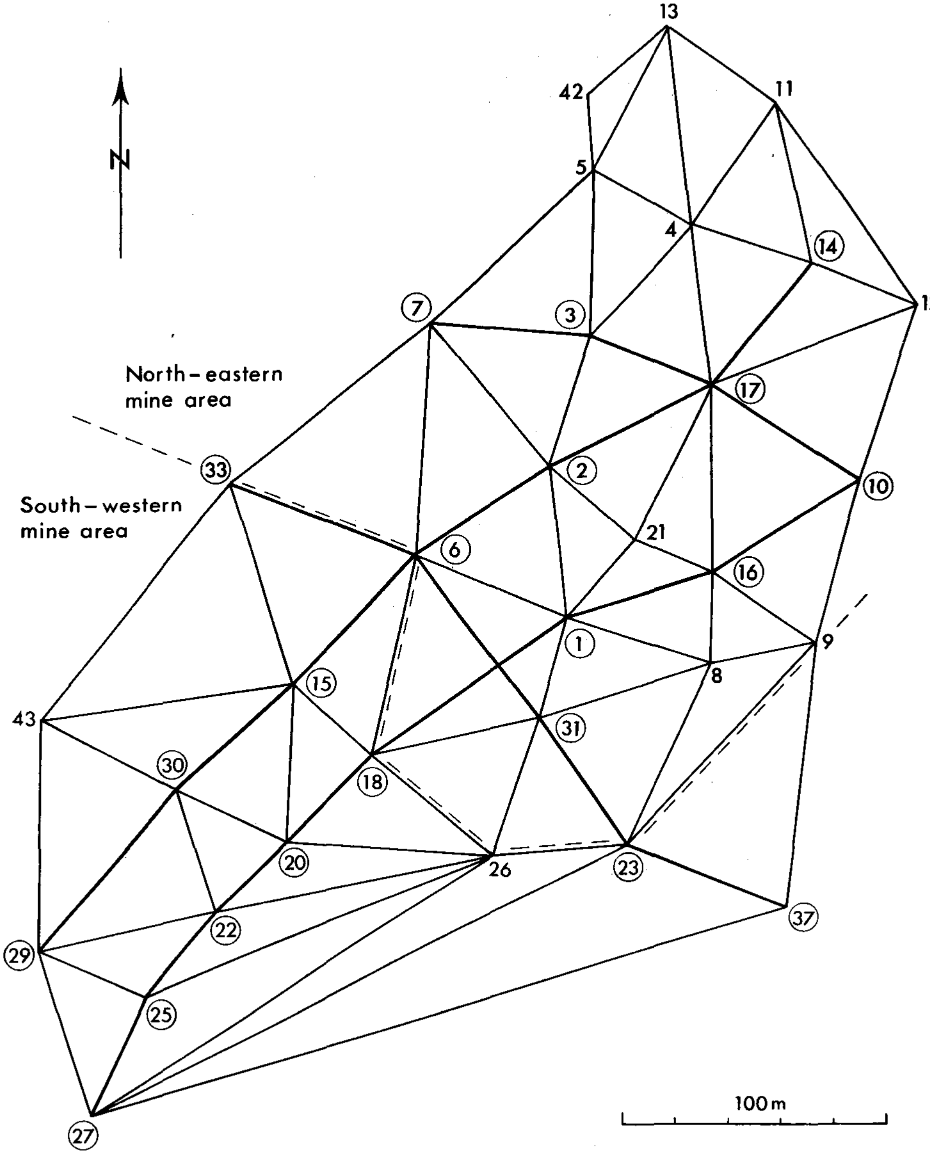


Fig. 6. The triangular net used in the calculation of the reserves of uranium. The drill holes shown in fig. 8 are marked with circles, the profiles of fig. 8 with thick lines.

which reflects the rolling forms of the sheet-like bodies of medium- to coarse-grained lujavrite (m-c lujavrite). The north-eastern area is topographically dominated by the resistant roof masses of gabbro and various volcanic rocks.

There appear to be several generations of m-c lujavrite, which all intersect all other rock types on the plateau (except rare lamprophyre dykes).

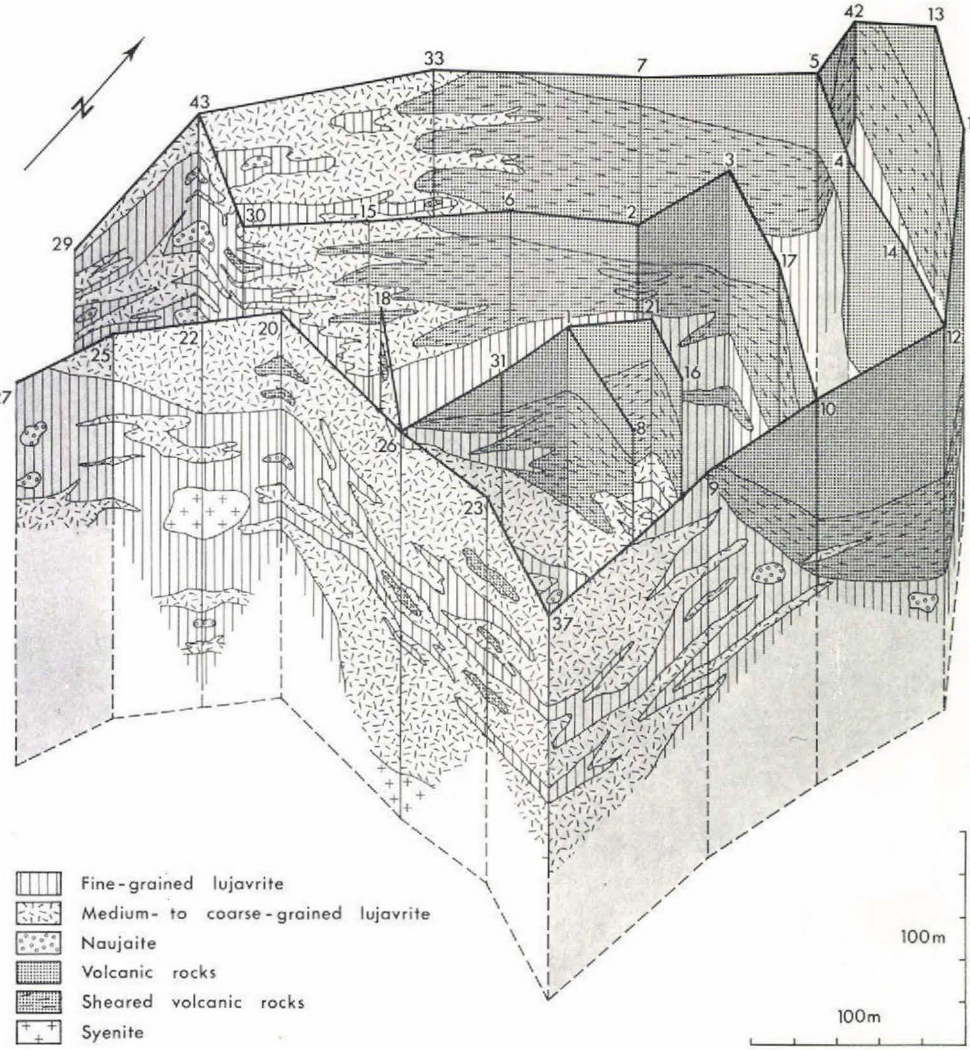


Fig. 7. Three-dimensional stratigraphic panel diagram (Bishop 1960) of the mine area. The position of the drill holes corresponds to their position on the location map (plate 1) and the depth of the layers in the panels is drawn with the plane of the map as datum horizon.

The main mass of m-c lujavrite outcrops on the plateau at altitudes of 600 to 620 m and runs as a weakly undulating 'blanket' down-slope towards the river. Drill holes nos. 34 and 36 are located in the lowermost outcrops, at an altitude of *c.* 400 m (plate 1). In the central part of the mass the m-c lujavrite is seen in drill holes to have a vertical extension of up to 200 m (fig. 8). The individual sheets of m-c lujavrite are generally less than 10 m thick, but may be up to 50 m

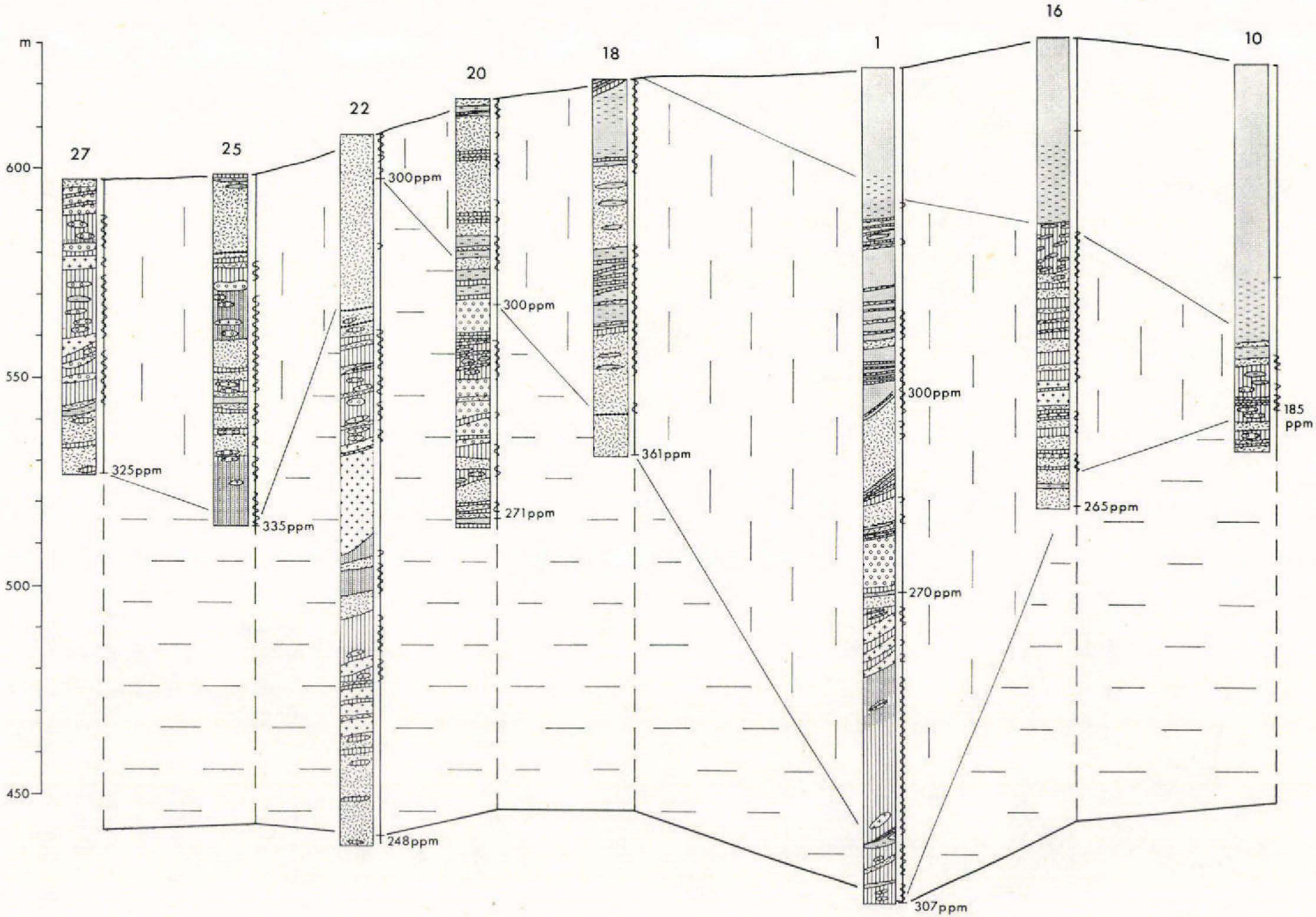
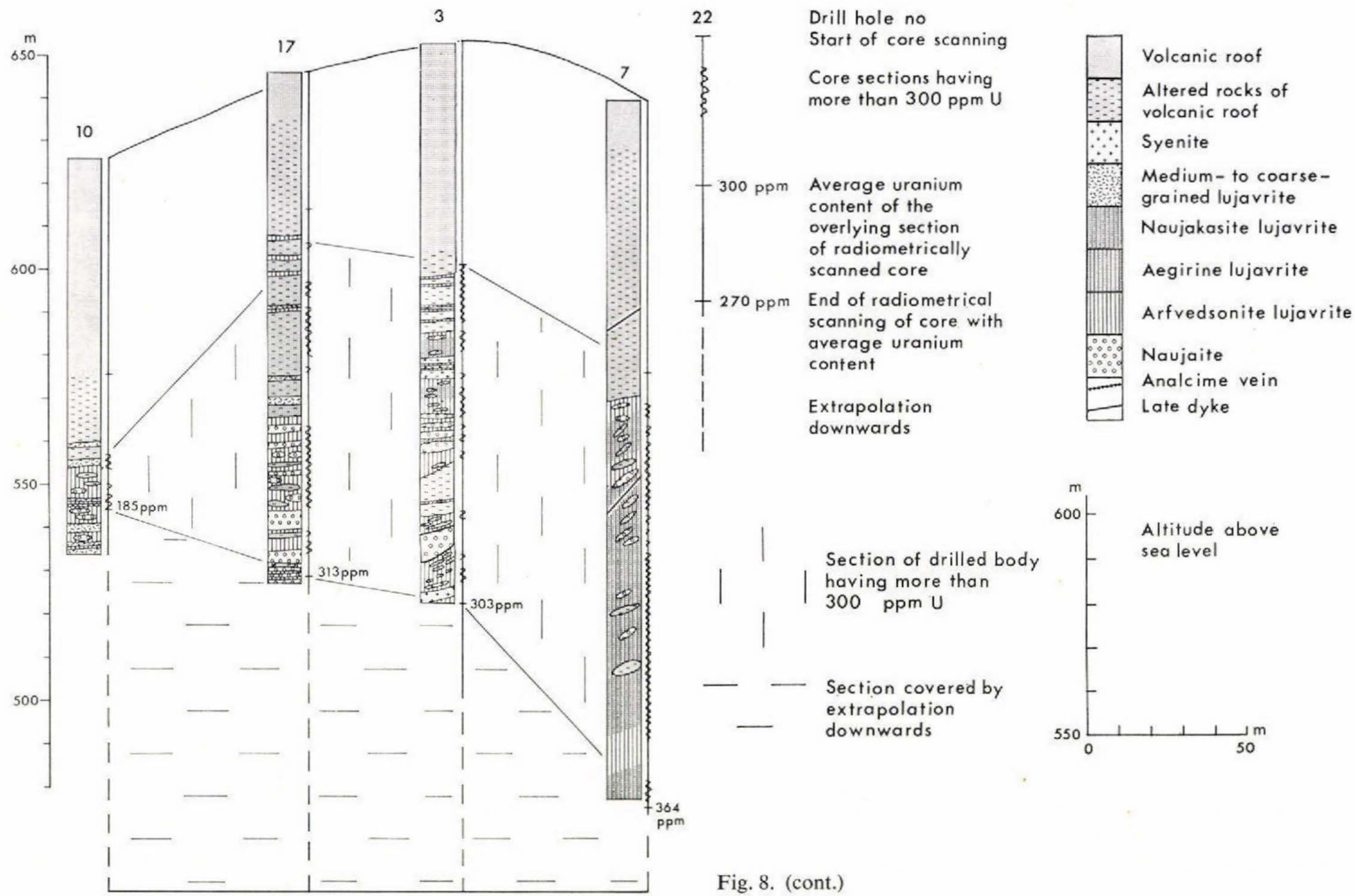


Fig. 8. Profiles through the mine area based on drill cores, cf. plate 1 and fig. 6. The vertical hatching represents the rock body with more than 300 ppm U; the horizontal hatching represents extrapolation of the ore body to depths exceeding those of the drill holes.



m
650
600
550
500
10
17
3
7
22
185ppm
313ppm
303ppm
364 ppm
Drill hole no
Start of core scanning
Core sections having more than 300 ppm U
300 ppm
Average uranium content of the overlying section of radiometrically scanned core
270 ppm
End of radiometrical scanning of core with average uranium content
Extrapolation downwards
Section of drilled body having more than 300 ppm U
Section covered by extrapolation downwards
Volcanic roof
Altered rocks of volcanic roof
Syenite
Medium- to coarse-grained lujavrite
Naujakasite lujavrite
Aegirine lujavrite
Arfvedsonite lujavrite
Naujaite
Analcime vein
Late dyke
Altitude above sea level
0
50

Fig. 8. (cont.)

thick in their central parts. The surface exposures indicate that the bodies are sheet-like or lens-like in form with a general south-eastern dip. They are mainly of a concordant nature, but dykes and apophyses are seen locally. Some of these wedge out downwards, as for instance at drill hole no. 27.

The contact zones between m-c lujavrite and the deformed and recrystallized volcanic rocks (with their sheets and veins of fine-grained lujavrite) consist of a heterogeneous migmatite-like assemblage of folded rocks (fig. 5) cut by veins of m-c lujavrite, m-c lujavritic pegmatites, analcime veins and nepheline-analcime veins (cf. Sørensen, Hansen & Bondesen, 1969). The last-named veins are rarely more than 1 cm wide and are rich in the water-soluble mineral villiaumite (NaF)

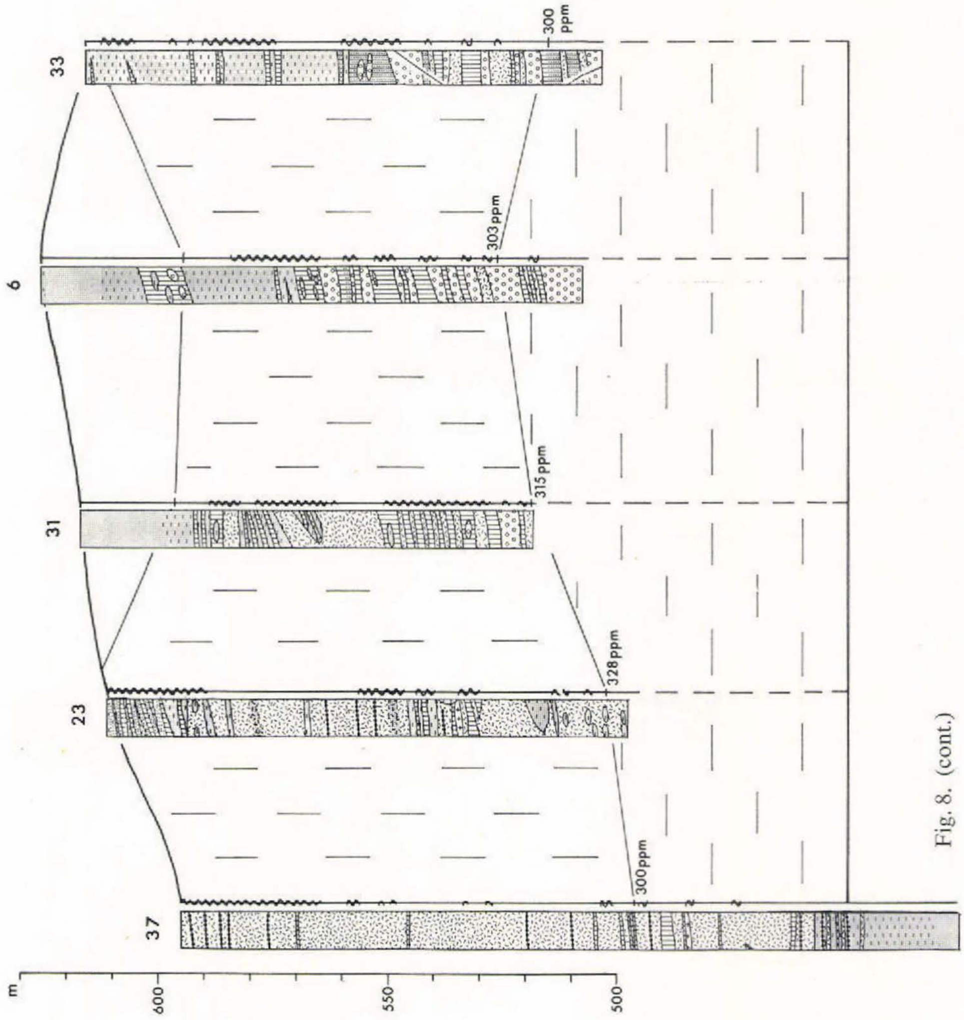
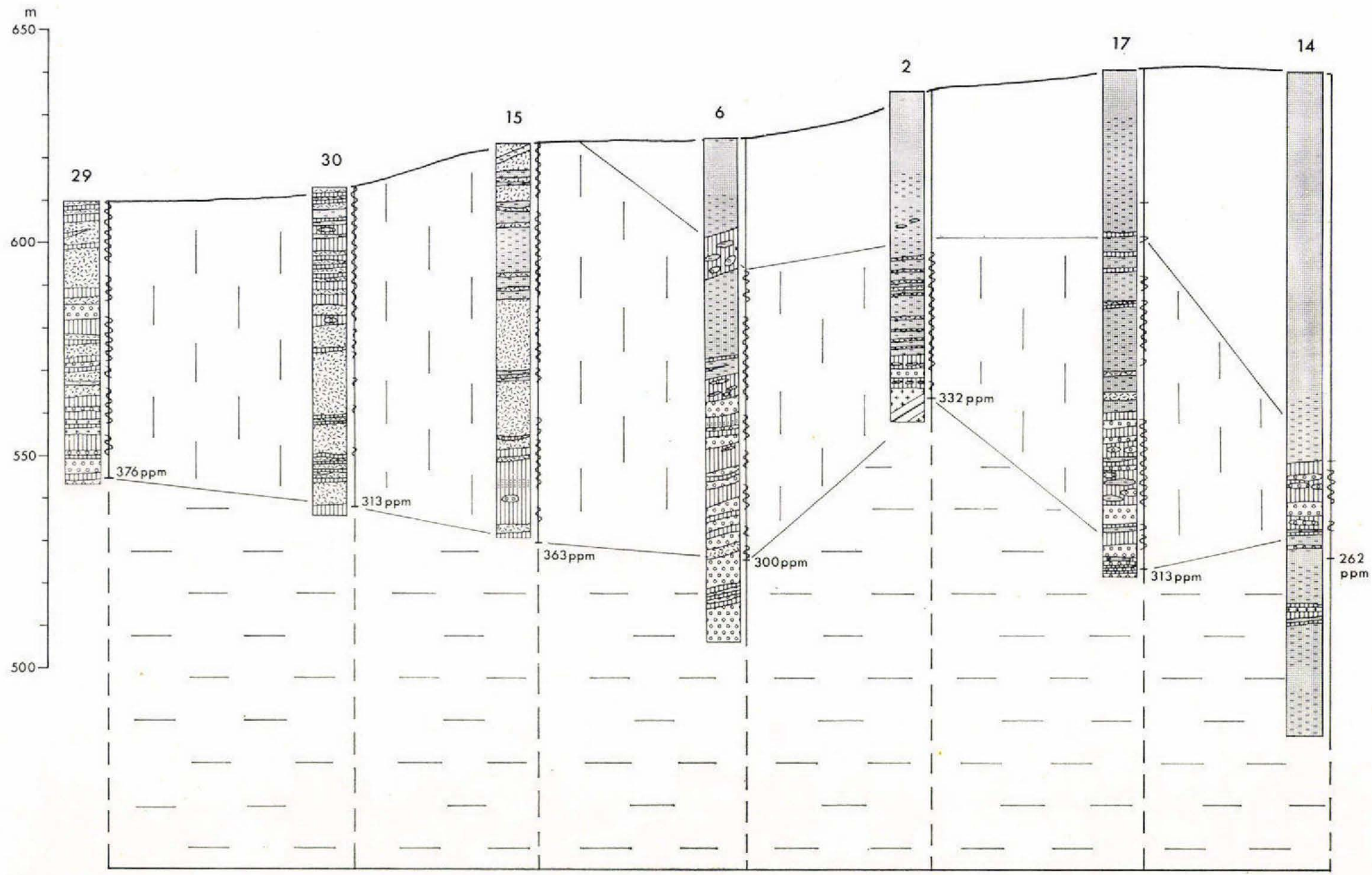


Fig. 8. (cont.)


m
650
600
550
500
29
30
15
6
2
17
14
376ppm
313 ppm
363ppm
300ppm
332 ppm
313ppm
262
ppm
Fig. 8. (cont.)

in the drill cores at depths greater than 50 m below the surface. These veins also contain sodalite, arfvedsonite, eudialyte, sphalerite, etc. The migmatite complex contains the highest concentrations of uranium.

The contact between the m-c lujavrite and the migmatite is often marked by pegmatitic zones rich in large grains of analcime and sodalite. The migmatite immediately outside this contact pegmatite is in places developed as a strongly radioactive breccia having rounded or angular grey patches up to a few centimetres across infiltrated by a network of thin fracture fillings of fine-grained arfvedsonite and by thin, white, analcime veins. The arfvedsonite network and the white veins are rich in steenstrupine.

Petrography of the medium- to coarse-grained lujavrite

No detailed studies of the m-c lujavrite have been published so far. The rock will therefore be briefly described at this place.

The rock is generally massive having plates of microcline, a few millimetres to about 3 cm long, set in a matrix made up of aggregates of fine-grained arfvedsonite prisms or needles. These aggregates often show a radiating arrangement of the arfvedsonite prisms.

In places the rock displays a fine layering, microcline-rich and nepheline-rich layers, both up to a few centimetres thick, alternate without showing any features of gravity stratification. The nepheline-rich layers have nepheline crystals set in a matrix of analcime and natrolite; arfvedsonite forms black spots, up to 2 cm across, made up of aggregates of fine needles. Also the microcline-rich layers may be rich in late or secondary analcime and natrolite.

Minor components of the m-c lujavrite are: sodalite, acmite, blue apatite, neptunite, sphalerite, britholite, Li-mica, sorensenite, pectolite, monazite and steenstrupine. Pseudomorphs after eudialyte are generally present, unaltered eudialyte less so. Villiaumite has been noted in drill cores.

The bodies of m-c lujavrite are rather heterogeneous in grain size and structure. There are many inclusions and screens of dense or fine-grained layered rocks which appear to consist of recrystallized volcanic rocks and fine-grained lujavrite. Some of these inclusions show internal fold structures of the type seen in the adjacent lujavrite-impregnated volcanics. The structures are conformable with the shape of the bodies of m-c lujavrite and with the layering of that rock.

Veins accompanying the medium- to coarse-grained lujavrite

The larger bodies of m-c lujavrite are accompanied by apophyses and pegmatite veins. The former often show peculiar internal fold structures due to the arrangement of clusters and schlieren of arfvedsonite. The pegmatites are often zoned with marginal zones rich in microcline, arfvedsonite, aegirine/acmite, steenstrupine and monazite, and cores of analcime with natrolite, albite, pyrochlore, 'igdloite', sphalerite, Li-mica, and beryllium minerals such as chkalovite, sorensenite, beryllite and bertrandite (cf. Semenov *et al.,* 1965; Hansen, 1968; Sørensen, Hansen & Bondesen, 1969; Sørensen, Danø & Petersen, 1971). These pegmatites are especially seen in the upper parts of the m-c lujavrite bodies; the lower parts have lenticular bodies of analcime rocks which in places appear to be altered xenoliths of naujaite.

There are also veins enriched in analcime in the marginal zones and in ussingite-albite in the cores. The veins may be rich in pyrochlore, 'igdloite', neptunite, blue apatite, chkalovite and in places in monazite, thorite and steenstrupine. Chalcothallite has been found in one of these veins. The veins are most common in the eastern part of the mine area where the bodies are from 0.25 to 1 m wide and 1 to 25 m long. They contain up to 20 vol. % of monazite (see p. 13 for a chemical analysis).

The uranium mineralization

The highest concentrations of uranium and thorium are found immediately outside and above the bodies of m-c lujavrite and especially in the migmatitic complex composed of altered volcanics, fine-grained lujavrite and numerous veins associated with the m-c lujavrite. The most extensive mineralized zone is the south-western exposed area which underlies an updoming of the volcanic roof that is an arched structure. Another large mineralized zone occupying an arched structure is intersected by drill holes nos. 1, 2, 3, 17, 16 and 21. A smaller arched structure is penetrated by drill holes nos. 23 and 31 (plate 1 and figs 7 & 8).

The depressions between these arched structures are underlain by very little m-c lujavrite and the complex of volcanics plus fine-grained lujavrite displays only traces of uranium mineralization.

The uranium mineralization is most complex, as is the geological structures. Only exceptionally is it possible to trace the same structure from one drill hole to its neighbouring holes. This is illustrated in fig. 8.

The uranium mineralized zones appear to be divided into slices by screens of volcanic rocks, partly in the form of nearly vertical dykes of trachyte and dolerite, which have survived the deformation and alteration accompanying the intrusion of the lujavrites. These screens have been met 200 to 300 m below the surface as for instance in drill holes nos. 37 and 38, which plunge respectively 75° and 70°.

The complex of volcanic rocks and fine-grained lujavrite is thoroughly altered in contact with the m-c lujavrite. Away from the bodies of m-c lujavrite the volcanic rocks are sheared and intruded by veins of fine-grained lujavrite. Adjacent to bodies of m-c lujavrite this mixture of volcanics and fine-grained lujavrite is deformed, in places folded (fig. 5), and metasomatically altered and recrystallized. The altered rocks are mainly made up of analcime and arfvedsonite. Nepheline is locally a major constituent but is often entirely missing. Eudialyte is present locally. Other components are epistolite-murmanite-lomonosovite group minerals, pectolite, neptunite, sphalerite, astrophyllite, Li-mica, albite, natrolite, garnet and in drill cores villiaumite. The radioactive minerals are only found adjacent to the m-c lujavrite.

The uranium mineralized zones vary in thickness from a few metres up to about 50 m. They have average contents of 300 to 600 ppm U and Th/U 3–4. Contents of uranium of more than 0.1 % are found in smaller areas. The field gamma-spectrometric survey gave average values of 538 ± 20 ppm U and Th/U 2.04 in the largest mineralized area (Løvborg *et al.,* 1971).

The altered complex of volcanics plus fine-grained lujavrite is enriched in U and Th not only adjacent to the larger bodies of m-c lujavrite but also near thin veins and veinlets. This is a general feature in the complex. Contrary to this there are no traces of uranium mineralization in syenite or naujaite cut by veins of m-c lujavrite. These rocks are, however, intersected by analcime-steenstrupine veins, and by veins of fine-grained lujavrite; the latter may be enriched in steenstrupine in the contact zones. There are no radioactive veins in the unaltered volcanic rocks.

Steenstrupine is the predominant radioactive mineral, thorite is important in restricted areas, monazite is widespread but occurs generally in smaller quantities than steenstrupine.

The Th/U ratio of the mineralized rocks is generally similar to that of steenstrupine. Lower ratios may be caused by uranium absorbed on pigmentary material, which forms various types of clusters, partly pseudomorphs after eudialyte. Unaltered eudialyte is practically lacking in the rocks carrying steenstrupine (Buchwald & Sørensen, 1961; Sørensen, 1962).

The contents of uranium in the m-c lujavrite vary from about 50 to about 500 ppm U, 100–300 ppm U being the most common. The Th/U ratio varies from 0.5 to 4. The content of U and the Th/U ratio decrease generally downwards in the bodies of m-c lujavrite (see table 4).

Table 4. Drill core no. 37: average values of U and Th/U

Depth in the core in metres	Content of U (ppm)	Th/U
0–38	500	3.2
0–50	460	3.2
0–60	407	2.8
0–110	308	2.5
0–150	273	2.1
0–160	268	2.0

Where several bodies of m-c lujavrite are intersected by one drill hole the lower ones show lower contents of uranium and lower Th/U ratios, the lowermost one having 50–100 ppm U and Th/U 0.4–1. Similarly, deep sections of altered volcanics plus fine-grained lujavrites have lower uranium contents than higher lying ones.

Large bodies of m-c lujavrite show occasionally a zonation so that the central parts have lower U and Th/U than the marginal parts.

The variation in Th/U may be caused by high contents of steenstrupine (with thorite and monazite) in the higher levels, while pigmentary material dominates at lower levels.

The fact that the volcanic rocks only rarely contain uranium mineralization adjacent to even large bodies of fine-grained lujavrite makes it likely that the major uranium mineralization of the mine area is genetically connected with the m-c lujavrite. This view is also corroborated by the increasing content of uranium upwards in the bodies of m-c lujavrite.

This indicates that uranium-bearing fluids have been given off by the melts which gave rise to the m-c lujavrite. These fluids have migrated towards culminations in the roof and have impregnated the adjacent rocks of the roof.

The uranium mineralization is thus found in fenitic exocontact zones and may be classified as contact metasomatic deposits. The uppermost bodies of the m-c lujavrite, which have contents of uranium of more than 300 ppm, also form part of the deposit.

The petrology and geochemistry of the m-c lujavrite and the uranium mineralization will be discussed elsewhere.

Radiometric measurements

Several radiometric techniques have been used in the evaluation of the uranium resources at Kvanefjeld. Until 1967, all field surveying and drill hole logging were made with geiger-tubes. The strong variation of the radioactivity of the lujavrites in the mine area at Kvanefjeld was outlined during an initial survey with geiger counters on a 5 m grid (Løvborg *et al.* 1968 a). The results are presented in fig. 9. In 1969 all the lujavrites on the Kvanefjeld area were measured with geiger counters (Sørensen, Hansen & Nielsen, 1969).

In 1966, a portable gamma-ray spectrometer for geological field work was constructed at Risø (Løvborg, 1967). The first field gamma-spectrometric measurements on the Kvanefjeld plateau were made with a 2×2" NaI (Tl) crystal as a gamma-ray detector. It was attempted to calibrate the spectrometer unit on the basis of a comparison between field measurements and contents of U and Th in rock samples collected at the measurement sites. The calibration constants derived were very inaccurate, mostly owing to the inhomogeneity of the Kvanefjeld rocks (Løvborg *et al.,* 1968 a).

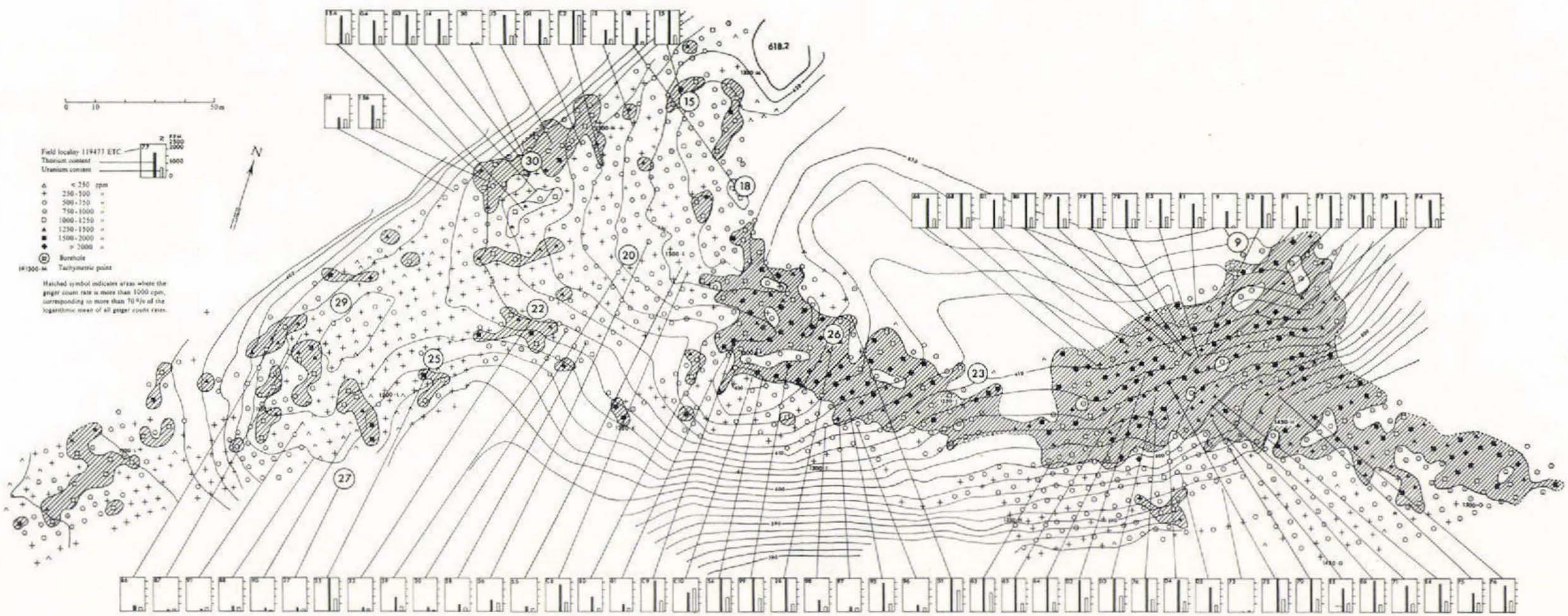


Fig. 9. Radiometric map of the south-western part of the mine area. Encircled numbers are the positions of the drill holes.

A successful application of field gamma spectrometry was made in 1969. This time the uncollimated 2×2" crystal had been replaced by a collimated 3×3" crystal calibrated against radioactive concrete cylinders constructed at Risø. Nine areas on the Kvanefjeld plateau were selected for intensive measurements. These were used for the construction of contour maps showing the distribution of U and Th in each area. Average contents of the two elements in nine different rock types were also derived (Løvborg *et al.,* 1971). Generally, it was concluded that portable gamma spectrometry is necessary in exploration of uraniferous rocks containing abundant and varying amounts of thorium (Løvborg, 1972).

In the laboratory, gamma-ray spectrometry was used both for non-destructive assessment of drill cores and for analysis of crushed hand samples. A special gamma spectrometer was designed at Risø for the core assessment. This instrument permits continuous or stepwise scanning of 3 to 4 cm drill core by gamma spectrometry (Løvborg *et al.,* 1972). The spectrometric core-scanning technique was considered more accurate than ordinary scintillation drill hole logging for an evaluation of the uranium resources at Kvanefjeld. In total about 3500 m of drill core from Kvanefjeld were scanned in the course of seven months, examples of diagrams are given in fig. 13. Diagrams of all drill holes are recorded in Sørensen, Rose-Hansen & Nielsen, 1971. The data obtained on the contents of uranium in the core form the basis of the grade and tonnage figures given in the next section.

Crushed hand samples from Kvanefjeld were analysed by means of a gamma spectrometer equipped with an automatic sample changer (Løvborg, 1972). Many of the samples were also analysed for uranium by spectrophotometry. Comparisons like these have indicated that the uranium in the Kvanefjeld rocks is in secular equilibrium with its daughters. The data from the mine area are given in fig. 9.

Calculation of the tonnages of uranium in the mine area

The uranium tonnage has been calculated within a 80 000 m² polygonal area (fig. 6). A total of 31 drill holes are located in this area.

Tonnages have been calculated separately for the south-western and the north-eastern parts of the mine area. In the first-named sub-area the ore crops out on the surface and the most detailed calculations are presented from this area. In the north-eastern sub-area, the ore is covered by non-radioactive layers of gabbro and volcanic rocks (plate 1 and figs 8 & 7).

The very complex rock distribution in the mine area is shown in the schematic south-west – north-east profile of fig. 10. The distribution of the rock types in the profile is only true on the drill hole sites. The boundary between the two sub-areas intersects the profile near drill hole no. 6.

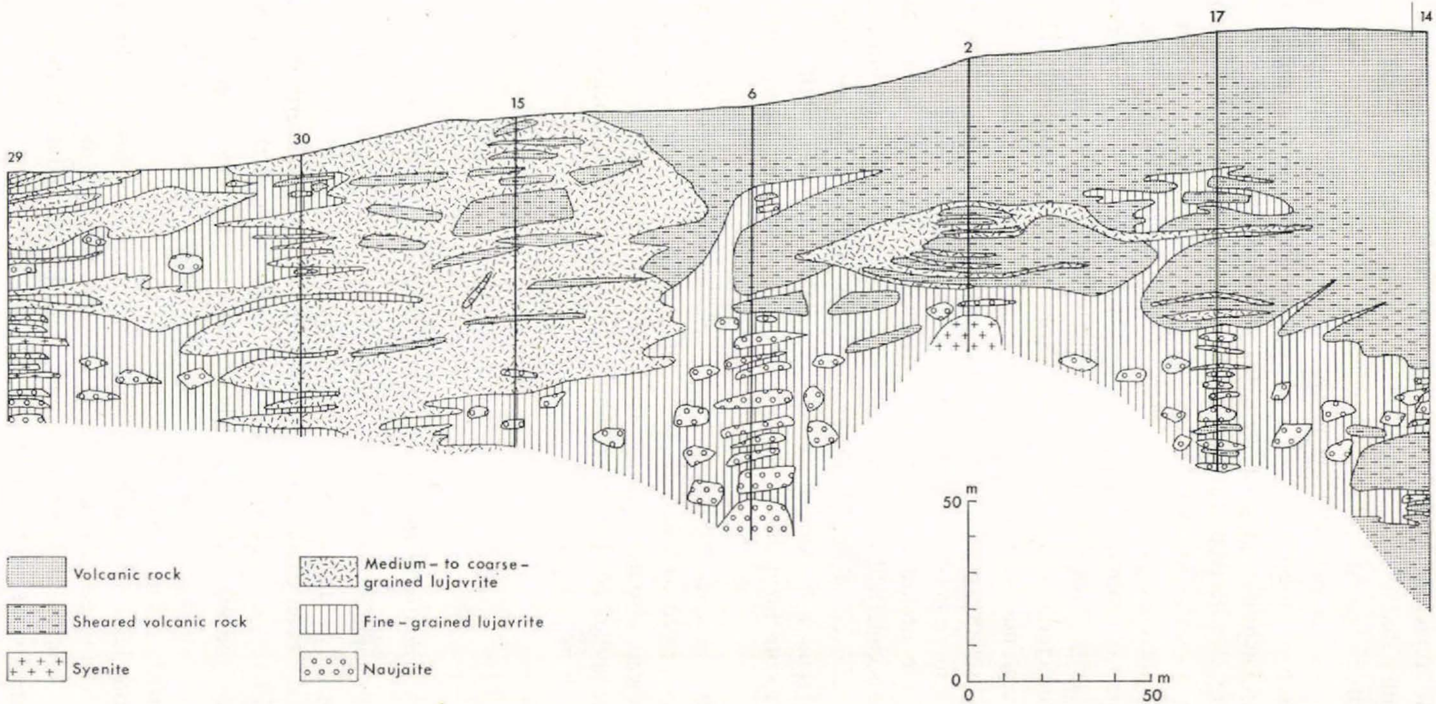


Fig. 10. Simplified schematic profile through the mine area. The distribution of the rock types is only true at the drill hole sites.

Method of calculation

In the choice of method for the tonnage calculations three important facts were kept in mind.

1. The radioactive elements are extremely unevenly distributed in the entire rock volume. This is mainly due to many weakly radioactive inclusions and to irregular zones and horizons of intense radioactive mineralization.
2. The uranium-thorium ratio is not constant which means that conventional total count gamma logging in the drill holes does not provide the basis for the tonnage calculations.
3. No deviation from secular equilibrium in the U^{238} series has been observed in drill cores or surface samples.

A drill core scanning system for gamma-ray spectrometric determination of uranium, thorium and potassium was developed at Risø and the contents of radioelements were determined in each linear metre of core (Løvborg *et al.,* 1972). The total count results from the core scanning procedure were in good agreement with the results from field gamma logging of the drill holes (Løvborg *et al.,* 1972).

In order to calculate the tonnage of uranium the investigated area was divided into 49 vertical prisms whose vertical edges were three consecutive drill holes (Forrester, 1946). The triangular net representing the base of the prisms is shown in fig. 6. Tonnage and grade were calculated for each prism by cumulatively combining the average uranium content of the basic triangle of each prism when traversing the length of the prism by one-metre steps. The calculations were based on the results of the scanning of the drill cores forming the vertical edges of each prism. All major calculations were performed on the GIER computer housed at Risø. The results of the calculations are recorded in tables 5–8.

The primary aim was to determine the size of an ore body with a grade of more than 300 ppm U. This cut-off grade was chosen on account of its proximity to the average grade of the lujavrites of Kvanefjeld. In this way the cut-off grade of the ore body was controlled first of all by the actual presence of lujavrite and secondly by the relative volume of inclusions and the tendency of decreasing grade with increasing depth.

Thorium

The calculations have only been performed for uranium, but the tonnages of thorium may easily be calculated using the same methods and programmes. A general impression of the amount of thorium can be achieved by multiplying the uranium figures by 2.6 which is the average thorium-uranium ratio for the rock body comprised by the core scanning.

Drill hole profiles

Figs 8a–d show vertical profiles in the mine area. Core sections containing more than 300 ppm U are indicated. The thickness of the non-radioactive cover rocks in the north-eastern area can also be seen from the profiles; it varies from 0 to 105 metres. The total amount of roof rocks within the polygonal area has been calculated on the basis of isopach constructions (Sørensen, Rose-Hansen & Nielsen, 1971). The rocks cover an area of 42 000 m^2 and constitute a volume of 1.3×10^6 m^3.

Extrapolations

The ore body defined by the prisms has been extrapolated both (1) vertically and (2) horizontally.

(1) The lujavrite-rich rock assemblage of Kvanefjeld is thought to be underlain by naujaite. The thickness of the lujavrite assemblage is indicated to be from 200 to 400 m. This is based on observations on the slope facing the valley and on drill hole no. 37, which intersects naujaite at a depth of 412 m.

The drill holes have been theoretically extended to a level about 100 m above the naujaitic substratum. The average altitude of the top of the substratum is calculated to be 335 m above sea level. The uranium grade in the extended drill holes has been estimated on the basis of the general trend (if any) of the grade in the drill holes in question and on the grade in the deepest holes. The amount of non-radioactive inclusions does not seem to increase with depth.

(2) The south-western part of the mine area is surrounded by radioactive rocks outside the polygonal area. The width of this zone varies from 10 to 100 m. This zone has been included in a horizontal extrapolation. The average thickness of the outer ore body was estimated to be 100 m, which is about 50 m less than the average thickness within the polygonal area. This is based on the lower topographical altitude to the south and the possibly smaller thickness of the radioactive rocks adjacent to the syenites to the west and north of the mine area.

Inclusions

The non-radioactive inclusions in the radioactive rocks consist mainly of naujaite and syenite, easily distinguishable from the lujavrites. The amount of inclusions is calculated in each prism and varies from 6 to 21 volume per cent averaging 10 per cent. Only inclusions comprising more than one metre length of drill core have been considered. The mean uranium grade in the inclusions is 50 ppm according to the scanning results.

Table 5. Reasonably assured ore reserves in the mine area

Area	Ore tonnage × 10^3 metric tons	Uranium tonnage metric tons	Ore grade ppm U
South-western sub-area	10368	3060	295
North-eastern sub-area	8200	2700	330
Total mine area	18568	5760	310

Table 6. Reasonably assured ore reserves in the mine area with subtraction of 10 volume percent non-radioactive inclusions

Area	Ore tonnage × 10^3 metric tons	Uranium tonnage metric tons	Ore grade ppm U
South-western sub-area	9330	3010	323
North-eastern sub-area	7380	2660	360
Total mine area	16710	5670	339

Table 7. Reasonably assured and estimated additional ore reserves in the mine area

Area	Ore tonnage × 10^3 metric tons	Uranium tonnage metric tons	Ore grade ppm U
South-western sub-area	23840	6820	286
North-eastern sub-area	24100	7600	320
Total mine area	47940	14420	301

Table 8. Reasonably assured and estimated additional ore reserves with subtraction of 10 volume percent non-radioactive inclusions

Area	Ore tonnage × 10^3 metric tons	Uranium tonnage metric tons	Ore grade ppm U
South-western sub-area	21460	6700	312
North-eastern sub-area	22000	7480	340
Total mine area	43460	14180	326

Results

Within the mine area tonnages and grades have been calculated for each triangular prism on the basis of the core scanning data. These tonnages can be classified as reasonably assured ore, that is without the vertical and horizontal extrapolations. Details about each drill hole, the position of the scanned sections, grades and tonnages of each prism etc. are not presented in this context.

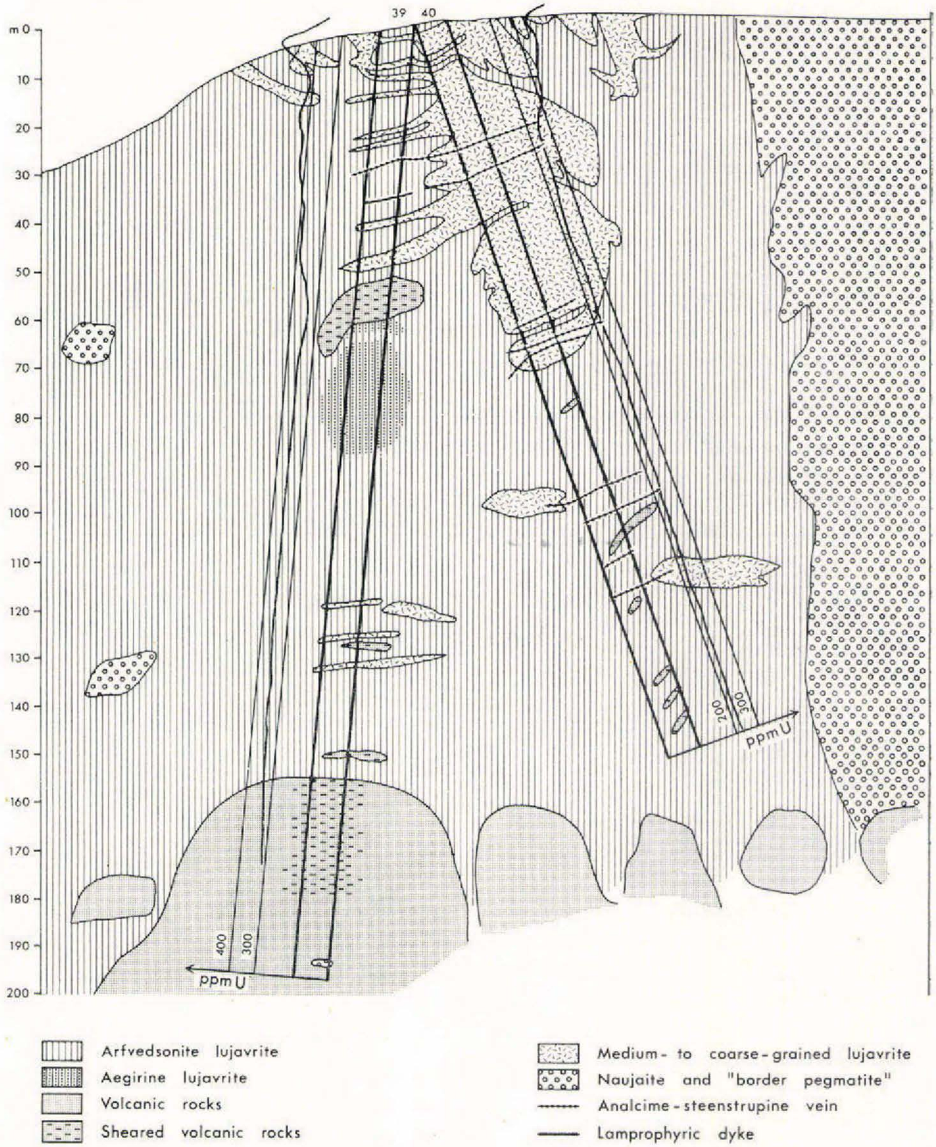


Fig. 11. Simplified schematic section around drill holes nos. 39 and 40.

These data can be found in Sørensen, Rose-Hansen & Nielsen (1971). In table 5 are listed ore tonnages, uranium tonnages and ore grades from the mine area made up of the south-western and north-eastern sub-areas. Table 6 shows tonnages and grades when 10 vol. % inclusions averaging 50 ppm uranium are subtracted. In tables 7 and 8 are listed tonnages and grades for the mine area when areas comprised by the vertical and horizontal extrapolations are included. These figures include reasonably assured and estimated additional ore reserves. All figures are given in metric tons and parts per million uranium metal. The density of the lujavrite is 2.8.

Uranium occurrences in the northernmost part of the plateau

General geology

The second largest area of radioactive rocks is found in the northernmost part of the plateau near the contact against the volcanic rocks (plate 1 and fig. 11). At this place the endocontact zone is made up of naujaite rich in pegmatites (= 'the border pegmatite'). The contact relations have been studied by Steenfelt (1972). The border pegmatite zone is poor in rare minerals and shows no concentrations of uranium or thorium.

The *naujaitic border pegmatite* is up to 30 m wide on the surface. Inside this naujaite there is a complex made up of several types of lujavrite. The lujavrites are rich in inclusions of naujaite, foyaite and strongly altered volcanic rocks.

The contact zone between naujaite and lujavrites is made up of a *greenish, medium-grained lujavrite* which is only weakly radioactive and which is considered to be a mixed rock formed by reaction between naujaite and the lujavritic melt. This lujavrite has closely spaced white analcime dots.

South of this hybrid rock there is a zone of *greenish to greenish brown lujavrite,* 25 to 50 m wide. The lujavrite is strongly laminated, the lamination dipping steeply towards the north. The rock is rich in aegirine/acmite and contains monazite, steenstrupine, sphalerite, Li-mica, fluorite, calcite, pseudomorphs after eudialyte and steenstrupine?, and other minerals. Nepheline is scarce. The lujavrite contains xenoliths of folded and altered volcanic rocks, and also inclusions of undeformed naujaite.

The lujavrite is cut by numerous veins of *green, medium- to coarse-grained lujavrite (green m-c lujavrite)* and by numerous pegmatites and light coloured veins. It is rich in acmite and felt-like aegirine adjacent to the veins of m-c lujavrite.

This *m-c lujavrite* is similar to that of the mine area with the exception that aegirine/acmite generally dominates over arfvedsonite giving the rock its green colour. This is especially the case in the northernmost part of the zone and in the uppermost parts of the drill cores. Arfvedsonite is the major dark mineral in the southernmost part and in the deeper parts of the drill core.

The green m-c lujavrite is rich in cloudy crystals of steenstrupine having 0.1 to 1.5 % U, Th/U 2–4 (Wollenberg, 1971). Monazite occurs as clusters of tiny crystals and as small crystals in aggregates of aegirine. In one analysed sample of monazite was found 0.1 % U, 1.3 % Th, Th/U 13 (Wollenberg, 1971). The rock further contains fluorite, sphalerite, pectolite, Li-mica, pseudomorphs after eudialyte, and a number of other minerals. There are in places concentrations of Li-mica and at the deeper levels of drill core no. 40 a good deal of biotite.

The *pegmatites* have marginal zones rich in microcline, and cores rich in analcime, sodalite and natrolite.

The *light coloured veins* are made up of analcime, sodalite, natrolite, beryllium minerals, sphalerite, steenstrupine, etc.

This *mixed zone of greenish lujavrite and green m-c lujavrite* is rather strongly radioactive. The gamma-spectrometric field measurements have shown that there are up to 1550 ppm U. Two areas measured gave average values of respectively 450 and 720 ppm U, Th/U 2.1 and 2.4 (Løvborg *et al.*, 1971).

The green m-c lujavrite is, as the m-c lujavrite of the mine area, less radioactive than the adjacent mineralized rocks. An average value of 260 ppm U, Th/U 3.0 has been determined by means of surface measurements (Løvborg *et al.*, 1971).

Towards the west the greenish lujavrite wedges out along the contact between the naujaitic border pegmatite and a rather *homogeneous, black, fine-grained lujavrite,* which is weakly radioactive with 280 ppm U, Th/U 1.54 (Løvborg *et al.*, 1971). On the surface this black lujavrite wedges out to the east about 150 m west of drill holes nos. 39 and 40 (plate 1, figs 11 and 13), but it is met in drill core no. 40 at a depth of 76.45 m, and continues from this depth to the bottom of the core at 162.10 m. This lujavrite is strongly laminated, the lamination dipping steeply towards the north.

South of the greenish lujavrite there is a wide zone of a crumbling, *brownish black, naujakasite-arfvedsonite lujavrite.* There are many large xenoliths of naujaite, foyaite and syenite and smaller xenoliths of volcanic rocks. The lujavrite shows steep lamination. It is intersected by only a few veins of green m-c lujavrite. This lujavrite contains in average 375 ppm U, Th/U 2.4.

Between the greenish lujavrite and the brownish black lujavrite there is a mixed zone made up of alternating bands of these two rock types.

The brownish black lujavrite has not been intersected by the drill holes. In no. 39 the core is from *c.* 60 to *c.* 157 m made up of a laminated arfvedsonite lujavrite with brown patches rich in acmite. This rock is fairly rich in steenstrupine and monazite and contains 200–400 ppm U, 500–800 ppm Th, Th/U *c.* 3. It is rich in villiaumite.

The uranium mineralization

Two drill holes were put down in this area in order to estimate the depth of the mineralized zone (plate 1 and figs 11 & 13). Both holes were drilled from the same platform, no. 39 directed to the south with a plunge of 85°, no. 40 towards the north with a plunge of 70° (fig. 13).

The veins of green m-c lujavrite are most numerous in core no. 39 between 0 m and 50 m but scarce veins are found at depths of about 130 m. This core has trachyte in its lowermost part. The trachyte is weakly mineralized in a thin zone adjacent to the overlying lujavrite.

Drill core no. 40 is dominated by green m-c lujavrite from 0 m to about 70 m. There is a concentration of uranium and thorium at the lower contact against the laminated rather weakly radioactive black lujavrite.

As there are only two drill holes it is not possible to give an exact figure for the quantity of uranium found in this area of fairly radioactive rocks. It is estimated that rocks with an average content of 350 ppm U underlie an area of about 300×60 m $= 18\ 000$ m^2. If the average thickness of the ore is taken to be 70 m this area contains about 1200 tons uranium in 3.5 million tons ore. This is believed to be a minimum figure for the amount of ore in this area.

The occurrences of uranium and thorium of the north-eastern part of the plateau

The north-eastern part of the plateau is mainly made up of the volcanic rocks of the roof; gabbro forming dykes and sills, together with trachytes and basaltic rocks (plate 1). In contrast to those of the mine area these rocks are fairly unaltered and the primary minerals are generally easily recognizable.

Fig. 12. Strongly deformed and recrystallized volcanic rocks and fine-grained lujavrite near drill hole no. 38.

The radioactivity of the volcanic rocks is very low. There are, however, linear zones of high radioactivity. These zones are characterized by strong deformation of the volcanic rocks in the form of shearing and folding (fig. 12). The volcanic rocks of the zones are also metasomatically altered and impregnated by veinlets of fine-grained lujavrite. Locally there are many thin analcime veins and veins of medium- to coarse-grained lujavrite.

The type of folding and the various types of veining are similar to the features of the mine area and it was therefore first believed that larger bodies of medium- to coarse-grained lujavrites could underlie these regions and that a uranium mineralization similar to that of the mine area could be found under this part of the plateau. Closer examination demonstrated, however, that this uranium mineralization is strictly associated with rather narrow zones of deformation and alteration in the gabbroic rocks. The drill holes nos. 38 and 42 both penetrate the mineralized rocks at shallow depths, 25 m and 10 m respectively below the surface (fig. 13).

The mineralized zones appear to form culminations or arches of folded and lujavrite-permeated, strongly altered rocks which downward pass into deformed and altered gabbro rich in epistolite-murmanite. This rock passes again into unaltered gabbro. The uranium mineralization may thus be interpreted from the scarce data available as coatings around blocks and masses of unaltered gabbro which may have foundered into the lujavrite magma.

The *radioactive rock* in this part of the plateau is grey to greenish and rich in dark schlieren dominated by arfvedsonite. The rocks are banded and the bands may be strongly folded. There are thin veinlets of steenstrupine-rich, fine-grained lujavrite and also thin veins of analcime containing steenstrupine and monazite. Eyes of analcime and sodalite are common.

The radioactive rock is made up of natrolite, analcime, arfvedsonite, acmite and steenstrupine with areas of sodalite and small laths of microcline and albite. There are minor amounts of astrophyllite, pectolite, Li-mica, neptunite, and yellow prismatic grains of an unidentified beryllium-rare earth silicate. Sphalerite is widespread, so is monazite in parts of these rocks. Locally the rocks are rich in nepheline.

The radioactive rocks have 400–800 ppm U and Th/U 2–4 (and up to 8), see Løvborg *et al.* (1971).

The fine-grained lujavrite veining these rocks is rich in small crystals of steenstrupine and is poor in eudialyte. Arfvedsonite, microcline and albite are the major minerals. Analcime, nepheline, sodalite and pectolite are often present.

The radioactive rock has on the surface been followed continuously from drill hole no. 38 to drill hole no. 33 (plate 1). It is generally a few metres wide; the depth is unknown. Attempts at intersecting the mineralized zone at depth have not been successful. A close set of drill holes is needed in order to elucidate the depth of this mineralization.

The altered gabbro in contact with the radioactive rock is rich in epistolite-

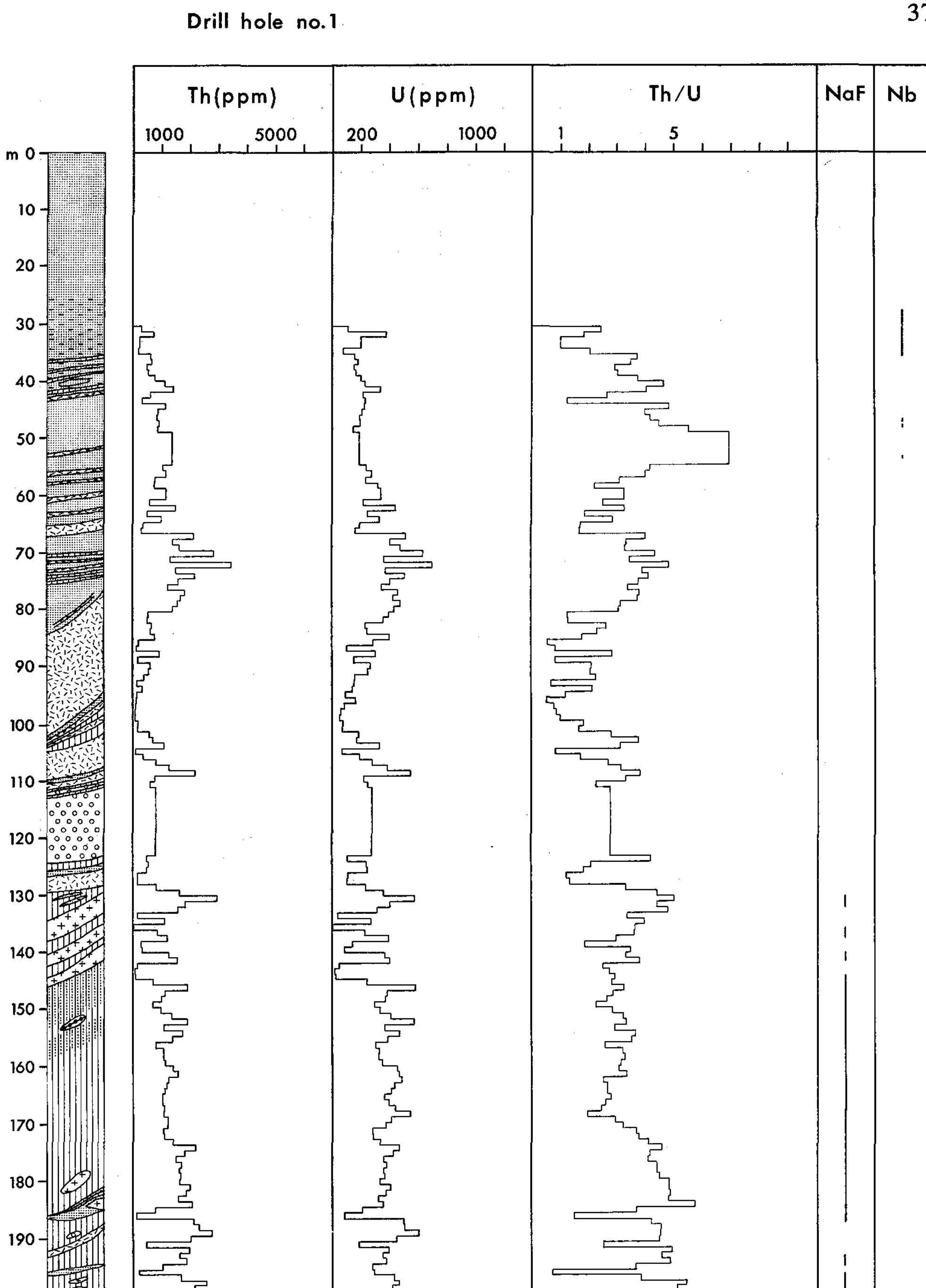
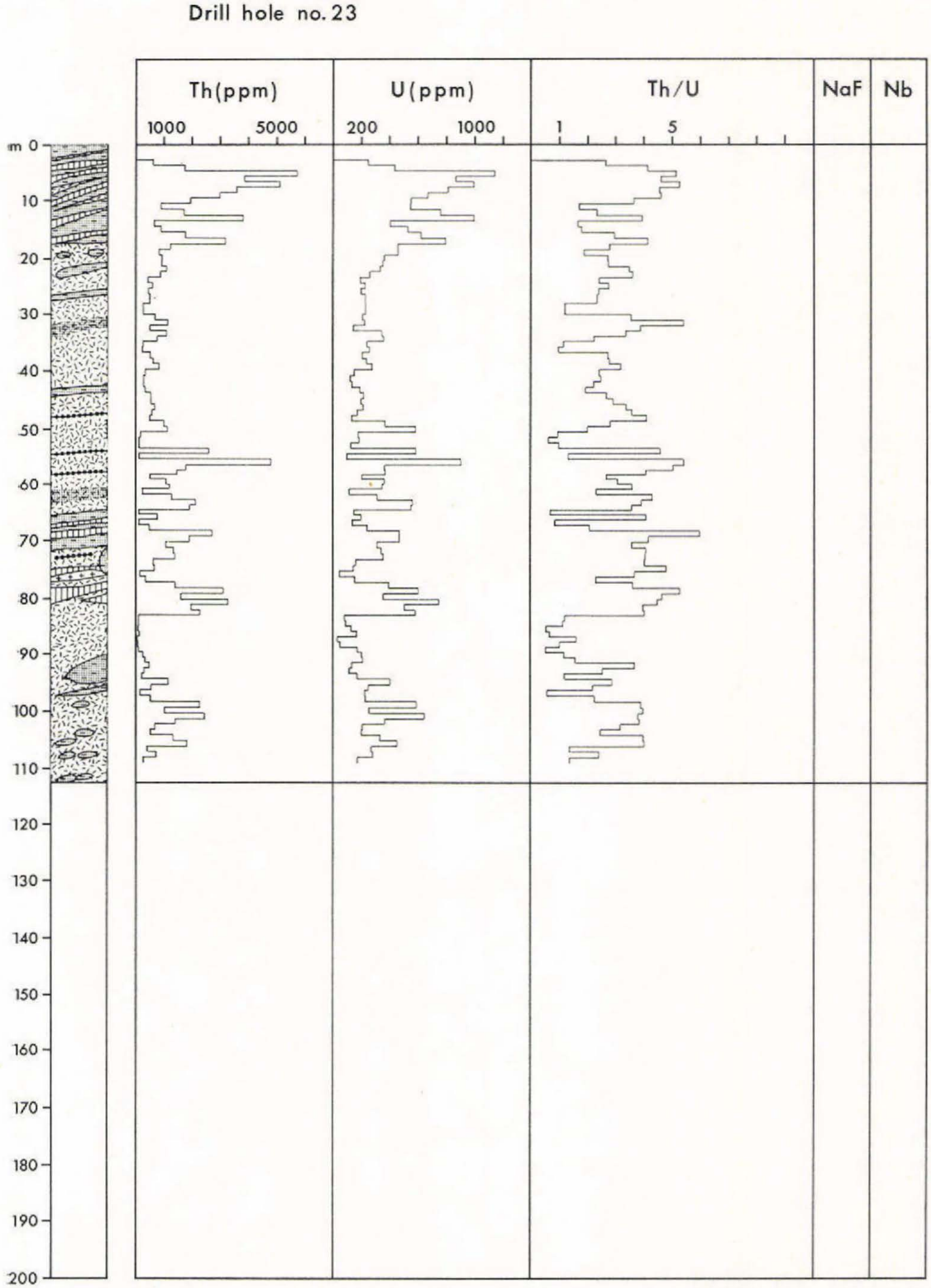
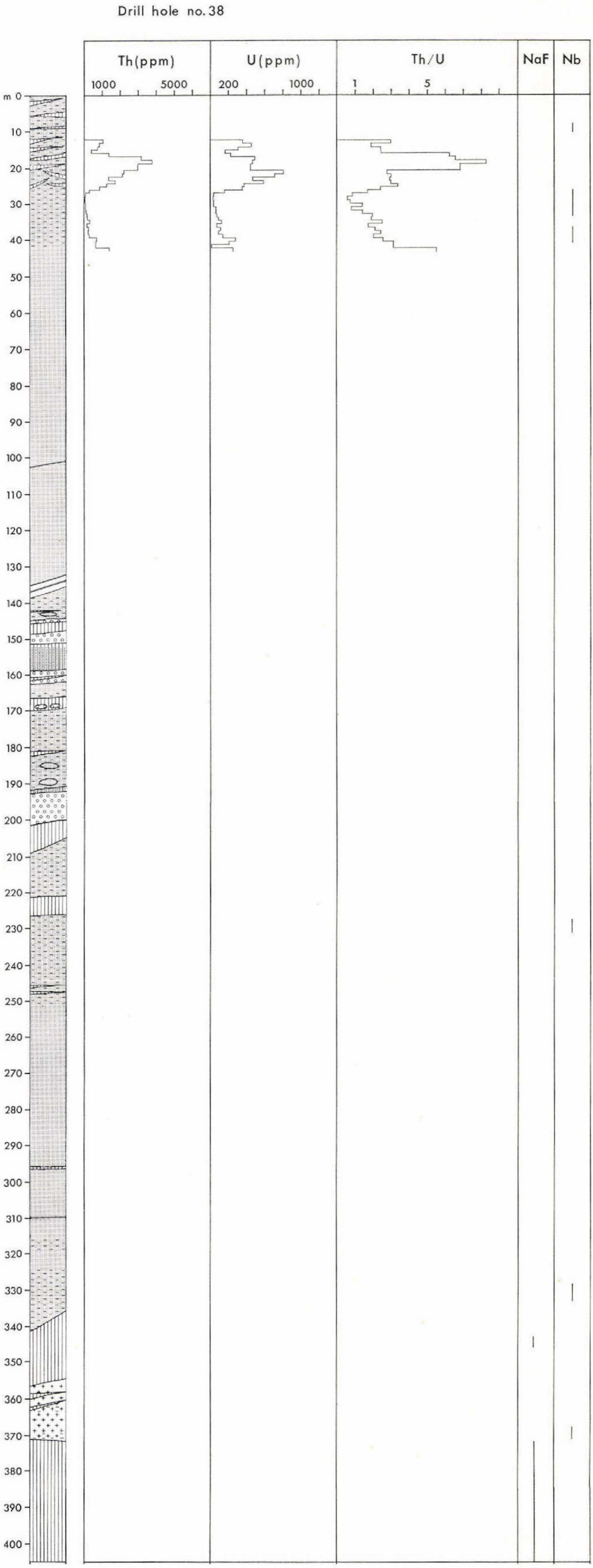


Fig. 13. Selected drill cores with indication of rock types, gamma-spectrometrical analyses, indications of occurrences of niobium minerals and villiaumite (NaF).

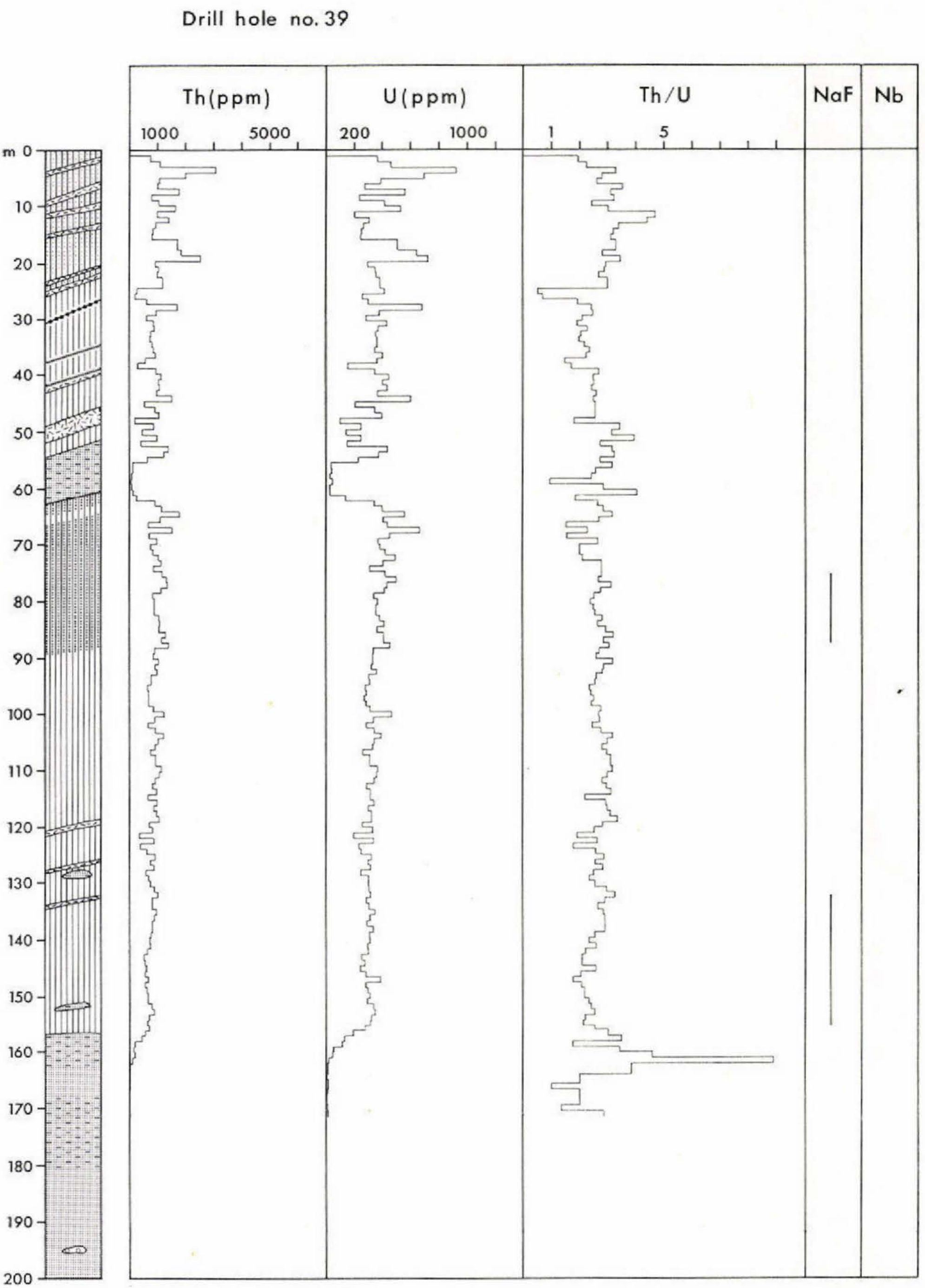
a. drill core no. 1. The hole is vertical. Note the Nb-mineralization just outside the zone enriched in uranium at ca. 30 m. Also note the strong uranium mineralization around veins of m-c lujavrite. The fine-grained lujavrite at the bottom of the core contains about 400 ppm U. The sheet of m-c lujavrite at 85 to 100 m shows decreasing contents of U and Th downwards.



b. drill core no. 23. The hole is vertical. Note the heavily uranium- and thorium-mineralized volcanic rocks at the top and the decreasing U and Th downwards in the m-c lujavrite at about 20–40 m.

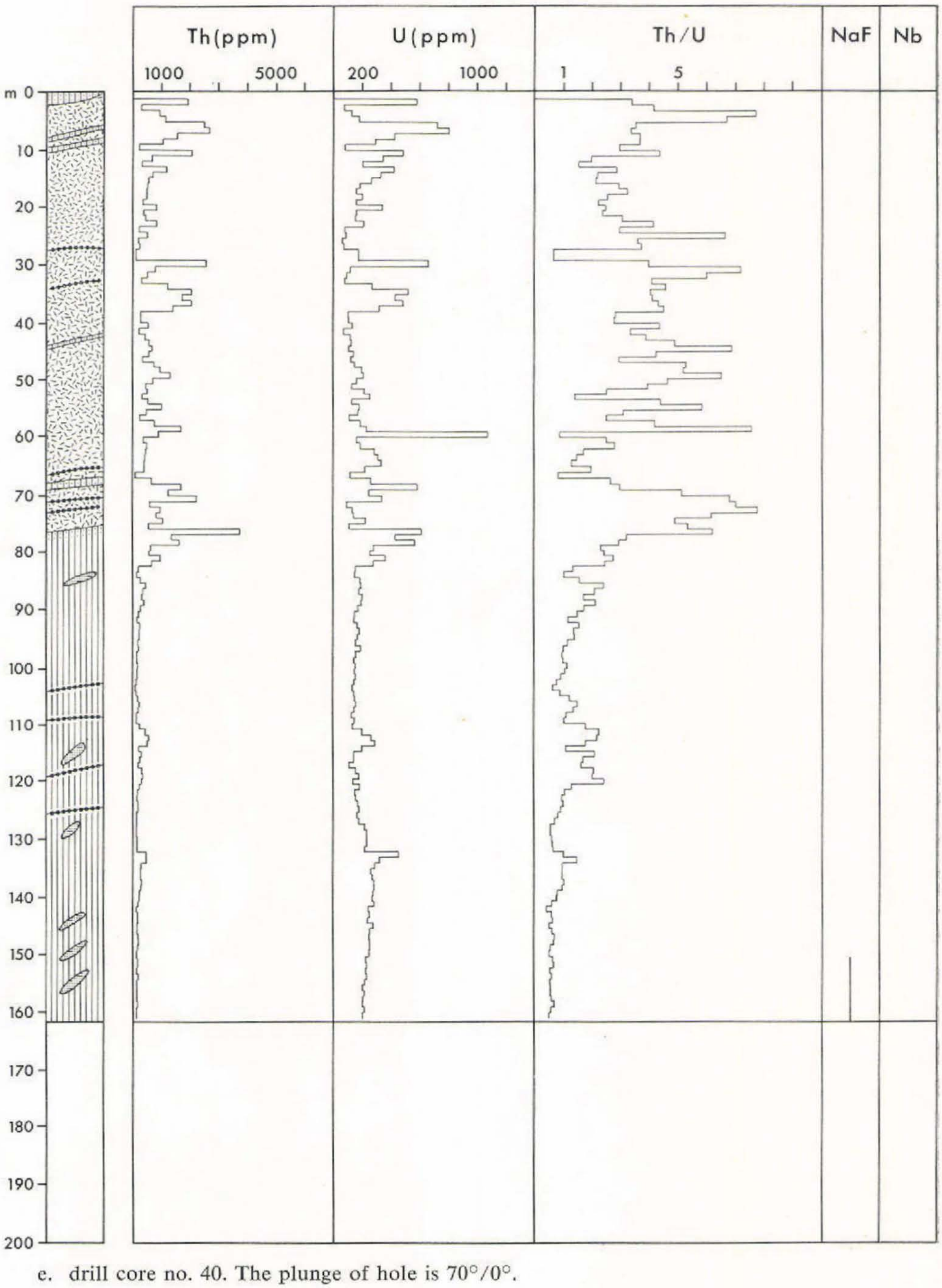


c. drill core no. 38. Only the uppermost part, with exception of the top part having a core diameter too big for the scanning apparatus, has been scanned gamma-spectrometrically. The plunge of the hole is 70°/62°.

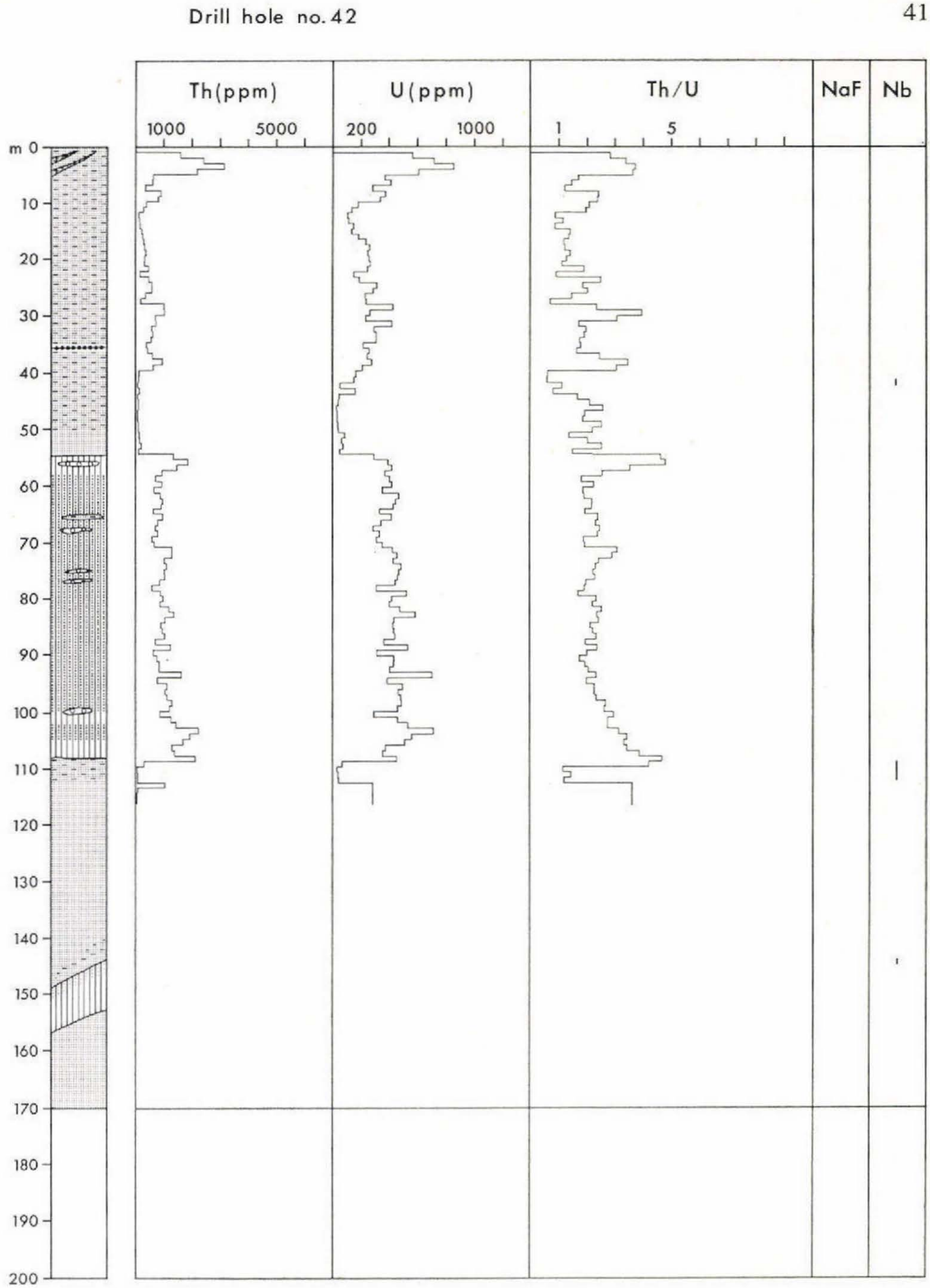


d. drill core no. 39. Plunge of hole = 85°/180°. Note that the lavas in contact with fine-grained lujavrites at 61 m and 157 m are not mineralized.

Drill hole no. 40



e. drill core no. 40. The plunge of hole is 70°/0°.



f. drill core no. 42. The plunge of hole is 70°/280°.
Note the very pronounced U–Th-mineralization near the top of the core in strongly altered and lujavrite permeated volcanic rocks. The volcanics in contact with fine-grained lujavrite at 54 m and 108 m are not mineralized. For legend see fig. 8.

murmanite, but very poor in radioactive minerals. It is intersected by thin veins carrying steenstrupine and monazite near the radioactive rock.

In drill cores 38 and 42 (fig. 13) it is seen that these radioactive rocks are underlain at depth by *fine-grained steenstrupine lujavrites*. These lujavrites have 400 ppm uranium and Th/U 2.5 to 3. They are rich in analcime and steenstrupine in contact with the volcanic rocks while the latter rocks are practically free from radioactive minerals near the lujavrite.

These features indicate that the uranium mineralization found in this part of the plateau is genetically associated with deeper-lying steenstrupine lujavrites. Fluids containing rare elements, including uranium and thorium, expelled from the crystallizing lujavrite have migrated to suitable sites of deposition. Deposition has taken place in deformed rocks having flat dips. It is a remarkable fact that the Th/U ratios of the radioactive rocks are similar to those of the lujavrite indicating that uranium as well as thorium have been mobile at the prevailing physical-chemical conditions.

The fine-grained lujavrites

As seen on the geological map of the plateau (plate 1) there are large masses of fine-grained lujavrites, for instance, in the westernmost part of the plateau. These lujavrites have locally 400 ppm U or more, but generally in thin veins. The fine-grained lujavrites exposed at the surface are thus not economically interesting with the exception of those found in the southernmost, northernmost and north-eastern part of the plateau.

The drill holes have, however, disclosed that large areas of the plateau may be underlain by steenstrupine lujavrites. The thickness and extension of this lujavrite is unknown.

DISCUSSION

The lujavrites of the Ilímaussaq intrusion have uranium contents higher than 100 ppm; in a number of areas 300 ppm or higher values. These uranium-bearing lujavrites have been discussed by Bondam & Sørensen (1959), Buchwald & Sørensen (1961), and Sørensen (1962, 1970a). The uranium mineralization of Kvanefjeld has also been discussed by Sørensen, Hansen & Bondesen (1969), Wollenberg (1971), Løvborg *et al.* (1971).

Uranium enrichment is principally found in lujavrites which, contrary to the common lujavrites of the intrusion, are free from eudialyte. The place of the eudialyte appears to be taken by steenstrupine and/or monazite. The rocks often have clusters of pigmentation which are interpreted as pseudomorphs after eudialyte.

The *steenstrupine-bearing lujavrites* found at several places in the intrusion are of *three main types*. The *first type* contains small crystals of steenstrupine occupying positions interstitial between the laths of feldspar. There is no or little analcime-natrolite. This type of steenstrupine appears to be a primary igneous constituent. The *second type* is the naujakasite lujavrite which may be fairly rich in steenstrupine (possibly primary). The *third type* is represented by lujavrites in which feldspars, nepheline and sodalite are substituted by analcime-natrolite. The steenstrupine of these rocks appears to be of late or post-magmatic origin.

The common lujavrites of the intrusion often have concentrations of large crystals of steenstrupine, in part poikilitic, in the contact zones around inclusions of naujaite. These crystals appear to be of late formation and may be associated with pseudomorphs after eudialyte rich in catapleiite (Sørensen, 1962).

Uranium concentrations are also found in *hydrothermal veins* associated with fine-grained lujavrites (Bondam & Sørensen, 1959, Sørensen, 1962).

These features indicate a genetic association between certain types of lujavrite and concentrations of uranium. The lujavrites are also distinctly enriched in uranium when compared with the other rocks of the intrusion (table 1). This is in agreement with the generally observed feature that uranium is enriched in the youngest, most alkali-rich rocks, of an igneous province or an intrusion. The concentrations of steenstrupine in altered lujavrites also recall the commonly observed increased contents of uranium in parts of igneous rocks altered by late or post-magmatic processes (cf. Sørensen, 1970b; Trofimov *et al.*, 1972).

The fine-grained lujavrites of the Kvanefjeld region are similar to the steenstrupine lujavrites found elsewhere in the intrusion. These lujavrites may be regarded as source rocks of the mineralizations.

The other three types of uranium mineralizations described in this paper are clearly epigenetic. The two types of deposits are associated with medium- to coarse-grained lujavrites intruding fine-grained lujavrites, volcanics, etc. The third type of uranium mineralization, that of the north-eastern part of the plateau, may also be associated with veins of m-c lujavrite in small areas but appears to be caused by mineralization of strongly deformed zones.

The uranium mineralizations are found especially under arched structures in the volcanic roof. The bodies of m-c lujavrites also show decreasing contents of uranium downwards. The favoured explanation of the mineralization is therefore that fluids expelled from lujavritic melts giving rise to fine-grained steenstrupine lujavrites and bodies of m-c lujavrite have migrated upwards and that uranium deposition has taken place in favourable structures and rocks. A part of the uranium (and other rare elements) may have been leached along the fractures percolated by the fluids.

This model is consistent with the commonly observed distribution of uranium in igneous rocks; the highest concentrations of uranium are commonly found in the highest levels of the intrusions, cf. Locardi & Mittempergher (1967), Locardi (1967), Sørensen (1970b) and Smithson & Decker (1973).

The geochemistry of uranium and thorium in the Ilímaussaq intrusion will be discussed elsewhere. Here should only be pointed out that future exploration for radioactive deposits in the intrusion may be based on the following criteria:

1. The uranium and thorium mineralizations are genetically associated with lujavrites,
2. Fluids containing uranium and also thorium have migrated upwards,
3. Deposition of uranium and thorium-bearing minerals takes place in favourable structures, principally in the arched structures in the volcanic roof rocks on top of lujavritic intrusions, besides zones of deformation containing folded rocks showing shallow dips,
4. Veins of medium- and coarse-grained lujavrites and thin analcime veinlets may be accompanied by U–Th mineralizations in favourable host rocks.

OTHER ELEMENTS

Niobium

Niobium minerals are widespread in the Ilímaussaq intrusion (Hansen, 1968; Semenov *et al.,* 1967; Semenov *et al.,* 1968). In the Kvanefjeld area they occur mainly in late hydrothermal veins and in sheared volcanic rocks and anorthosites.

Hydrothermal veins. Pyrochlore and 'igdloite' (in the following named together as pyrochlore) are mainly found in the uppermost part of the m-c lujavrite. They occur in veins and in more or less regular bodies which are from a few millimetres to about 2 m wide and from a few centimetres to many metres long. The veins have very variable strike and dip.

The pyrochlore-bearing veins of the mine area have been mapped in detail by J. Hansen and J. Metcalf-Johansen. They make up about 10 % of the surface area and contain from less than 1 % to about 20 % pyrochlore. The pyrochlore contains about 60 % Nb_2O_5 which means that the veins have up to 12 % Nb_2O_5. More than 200 field determinations with isotope fluorescence instruments (EDX or Energy dispersive X-ray) (Wollenberg, Kunzendorf & Hansen, 1971) combined with chemical analyses on surface samples of vein material give an average of 0.8 % Nb_2O_5 in the veins.

The drill cores show a decreasing content of pyrochlore-bearing veins downwards. The amount of pyrochlore in the veins also decreases with depth and an estimation of the niobium content based on visual evaluation combined with EDX analyses and chemical analyses have given in the three dimensional model an average content of 4 % vein material with 0.5 % Nb_2O_5 which corresponds to an average content of 0.02 % Nb_2O_5 in the complex of m-c lujavrite. The mass of m-c lujavrite with these pyrochlore-bearing veins amounts in the drilled area to about 8×10^6 tons which gives about 1600 tons of Nb_2O_5 or 1100 tons of Nb. The ratio Nb/Ta in pyrochlore is 100–200 (Hansen, 1968) corresponding to 5.5–11 tons of Ta.

Niobium in sheared rocks. The unaffected volcanic, syenitic and anorthositic rocks of the Kvanefjeld area have very low contents of niobium and tantalum (Hansen 1968; Gerasimovsky, 1969). Where these rocks are sheared in contact with the fine-grained lujavrites they are metasomatically altered and often contain murmanite (Hansen, 1968). The content of murmanite varies from less than 0.01 % to more than 20 % of the volume of the rocks. The grain size is from less than 1 mm to 1 cm. On the surface of the Kvanefjeld plateau niobium mineralization of this type occurs over extensive areas, especially outside the zones of uranium mineralization. The niobium mineralization will be described in detail in another paper.

Even if the uranium ore is poor in this type of niobium mineralization and uranium minerals are very rare in the niobium-rich rocks, niobium is a potential byproduct in possible future exploitation of the uranium. The tonnage of murmanite minerals has consequently been calculated in the mine area. The area considered is bounded by the following drill holes: nos. 42, 13, 11, 12, 10, 37, 31, 15, 33, 6, 1, 21, 17, 4, 42 (plate 1 and fig. 6).

In the calculation, which is based on the drill cores, only areas with 0.1 % Nb_2O_5 or more are used. The quantity of niobium minerals was estimated visually and measured with EDX analyses, XRF and chemical analyses. The EDX apparatus has been described by Kunzendorf (1971, 1973).

The procedure used here is described by Kunzendorf *et al.* (1973). Niobium in rocks with 0.1 % Nb_2O_5 or more is estimated to be about 5000 tons.

Villiaumite (NaF)

Villiaumite, which was first described from the Ilímaussaq intrusion by Bondam & Ferguson (1962), is widespread in lujavrites and naujaites. The amount is from accessory to *c.* 20 vol. %. The grains are predominantly from less than 1 mm to *c.* 3 mm across; grains up to 1 cm are found. Villiaumite is water soluble and has only been found in the drill cores at depths greater than 50 m below the surface.

As villiaumite is considered a potential byproduct in the possible exploitation of the uranium, the amount of villiaumite present in the mine area has been calculated.

The calculation of the quantity of villiaumite is made on the basis of chemical analyses and on visually estimated contents on drill cores. Only areas with more than 0.5 % NaF have been used in the calculation. The area considered is bounded by the following drill holes: nos. 13, 42, 3, 6, 15, 20, 22, 25, 37, 23, 26, 16, 12, 11, 13 (plate 1 and fig. 6). A detailed description of the procedure is given in Kunzendorf *et al.* (1973). The calculation has given a total of 21 000 tons NaF or 10 000 tons F in rocks with more than 0.5 % villiaumite.

Analyses of the drainage water from the Kvanefjeld area show that NaF is an essential part of the dry matter left after evaporation. The brooks of the area carry on the average *c.* 1 m^3/sec of water containing 2.5 ppm of F (Lundgaard & Sørensen, 1965 and L. B. Larsen, 1973), which amounts to 80 tons F or 175 tons NaF per year. It is assumed that villiaumite from the surface and down to a depth of 50 m has been dissolved by percolating water. Supposing that the NaF originates from the rocks of the Ilímaussaq intrusion, which cover about 10 km^2 of the local drainage area, the present leaching rate corresponds to 17.5 g NaF per m^2 per year.

The drill cores from Kvanefjeld indicate that the villiaumite is very unevenly distributed so that local higher concentrations of NaF probably occur also outside the considered area. In fact villiaumite has been found in drill cores from other parts of the intrusion.

Flotation of villiaumite. It has been shown that villiaumite can be concentrated by flotation with oleic acid and similar type anionic collectors, in spite of the fact that the mineral is rather easily soluble in water. This is probably due to the formation of a water repellent coating which inhibites the process of dissolution. However, losses are inevitable, but can be reduced to less than 20 % by the use of kerosene as an auxillary collector.

By addition of NaOH to the pulp all other minerals than villiaumite are depressed.

Beryllium

Beryllium minerals such as chkalovite, sorensenite, tugtupite, beryllite and bertrandite are found in pegmatites and veins in and adjacent to the m-c lujavrite. Beryllium minerals are also found in veins associated with the fine-grained lujavrite. The veins are from a few millimetres to *c.* 50 cm (and up to 1 m) wide and can be followed a few centimetres to several metres (Sørensen, Hansen and Bondesen, 1969; Andersen, 1967; Engell *et al.*, 1971; Sørensen *et al.*, 1971).

More than 60 field determinations with beryllometers (Løvborg *et al.*, 1968 b; Engell *et al.*, 1971) combined with chemical analyses and beryllometer analyses of surface samples and samples from drill cores have given an average content of 0.01 % beryllium oxide in the veins of the mine area. A vein 0.5 m thick just north of the mine shaft, which can be followed for *c.* 20 m contains about 0.5 %.

Beryllium minerals are widespread in hydrothermal veins in the Ilímaussaq intrusion. The highest concentration found so far occurs on the slope between Taseq and Narssaq Elv (Engell *et al.,* 1971). The most important beryllium mineral is here chkalovite but several others have been found. The beryllium minerals are found in thin veins and zones ranging from about 1 mm to 2 m wide. The beryllium mineralization on the Taseq slope is about 500 m long and up to about 200 m wide.

Beryllometer measurements indicate only small areas with an average concentration of 0.1 % BeO or more (see Engell *et al.,* 1971).

Zirconium

Zirconium is mainly found in eudialyte which is a common mineral in sodalite foyaite, naujaite and some of the fine-grained lujavrites and is very important in special layers in the kakortokites south of the Kangerdluarssuk fjord (table 1, fig. 2).

The reserve in the kakortokites situated above sea level has been recalculated from Bohse, Brooks & Kunzendorf (1971) to be 61×10^6 tons of ZrO_2 in 43×10^8 tons ore. Besides that there is a considerable reserve below sea level. The average content of ZrO_2 in the kakortokites is 1.2 %, but there are huge amounts of ore with average contents of more than 2 %; locally up to 8 %.

As the ratio ZrO_2/Nb_2O_5 is 9.5 in the kakortokites the reserve of Nb_2O_5 is 6.5×10^6 tons.

Zinc

Zinc is predominantly found in sphalerite, a common mineral in the agpaitic rocks of the intrusion, especially in the m-c lujavrite and the black lujavrite. The black lujavrite has on average 2074 ppm Zn (Gerasimovsky, 1969), the m-c lujavrite 2100 ppm Zn.

Lanthanides and yttrium

Rare earth elements occur mainly in monazite, steenstrupine, rinkite, and eudialyte (table 2). The highest contents of rare earth elements are found in the black lujavrite and in the m-c lujavrite, the average content being 7750 ppm and 6100 ppm respectively (Gerasimovsky, 1969). The average contents of RE in the major rock types of the intrusion are given in table 9.

An analysis of the flotation concentrate of the radioactive rock gave ΣRE 8.1 % (CeO_2 43 %, Nd_2O_3 11 %, Pr_2O_3 3.7 %, Eu_2O_3 0.08 %, Sm_2O_3 1.1 %, Y_2O_3 4.5 %, La_2O_3 36.6 %).

Table 9. Rare earth elements in the major rock types of the Ilímaussaq intrusion

figures are average contents in ppm (from Gerasimovsky, 1969)

	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Yb	Y	Ce/Y
sodalite foyaite	270	518	63	220	43	6.0	39	6.8	23		14.5	11.0	125	5
naujaite	166	305	33	140	28	6.3	21		16.5		9.3	7.9	95	4.2
kakortokite, red	725	1280	185	680	165	27	145	28	140	35	90	80	800	2.3
kakortokite, white	330	535	60	232	40	5.2	36	6.8	26	7	18	14	175	4.2
kakortokite, black	210	365	47	187	39	4.3	37	6.2	35	6.3	26	22	260	2.1
kakortokite, average	330	550	65	250	48	6.7	43	8.0	35	9	24	19.5	225	3.4
lujavrite, green	870	1530	210	760	130	18	145	34	100	24	75	60	750	2.9
lujavrite, black	2280	3330	330	900	134	19	120		87		50	40	48	8.8
m-c lujavrite	2100	2300	310	810	120		73		57		24	8	240	13

Lithium, rubidium, cesium and gallium

Lithium is predominantly found in lithium mica containing about 4 % Li, but also arfvedsonite is relatively rich in lithium having up to 1015 ppm. All the rocks of the intrusion have high contents of lithium with an average of 791 ppm in the black lujavrite and 1192 ppm in the m-c lujavrite.

The rubidium content of the lithium mica is 5960–6230 ppm. The green lujavrite contains 560 ppm Rb, the black lujavrite 630 ppm Rb, and the m-c lujavrite 1200 ppm Rb (Gerasimovsky, 1969).

The m-c lujavrite contains 72.5 ppm Cs, the black lujavrite 20 ppm Cs and the green lujavrite 5 ppm Cs.

The gallium content of the albite is 220–300 ppm. The green lujavrite contains 132 ppm Ga, the black lujavrite 104 ppm Ga, and the m-c lujavrite 72.5 ppm Ga (Gerasimovsky, 1969).

PROPOSED METHOD FOR THE RECOVERY OF URANIUM FROM THE KVANEFJELD DEPOSIT

Introduction and preliminary studies

The Kvanefjeld uranium ores are not suitable for extraction by the standard method of leaching with dilute sulphuric acid as the radioactive minerals of Kvanefjeld are less attacked by the acid than the associated felsic minerals such as analcime, sodalite, natrolite and nepheline. A small fraction (*c.* 30 %) of the uranium in the ore can be obtained by acid leaching. This comes mainly from the pigmentary material which is found in the dust after grinding and as a coating on other minerals. The leach liquor is very poor in uranium and contains unacceptable amounts of colloidal silica. Experiments with carbonate leaching and pressurized leaching also proved unsuitable. Concentration by flotation and magnetic separation has given limited success as there is considerable loss of uranium with the tailings (Sørensen & Lundgaard, 1966).

Two hundred tons of rock were mined as the basis of the large scale laboratory work. It should be noted that it did not truly represent the average ore quality as the adit cut through a part rich in monazite, steenstrupine, pyrochlore, sphalerite and sorensenite containing up to 700 parts per million of uranium. The ore is so heterogeneous that it is practically impossible to obtain a representative sample in only one adit.

Recovery

Sulphating roasting is the only technically applicable method that has so far proved effective in extracting the uranium from the ore. In this process the ore is treated with SO_3 at about 700° C. Subsequent leaching with water yields up to 70 % of the uranium as dissolved sulphate, depending on ore composition and absorption of SO_3 (Asmund *et al.,* 1971). Compared with extraction by acid leaching the sulphating roasting method yields a higher uranium recovery and prevents silica from being dissolved in the liquor.

The arfvedsonite in the rock acts as a catalyst for the reaction $2\,SO_2+O_2=2\,SO_3$. Owing to the ubiquitous dissemination of arfvedsonite in the ore it is possible to use SO_2 + air as the sulphating agent.

All observations indicate that uranyl sulphate formation occurs only on the mineral surfaces implying a diffusion of metal through the solid crystal. The selectivity obtained in sulphating a mixture of minerals may then be explained by their different crystal structures. Advantage is further derived from the relatively high thermal stability of uranyl sulphate.

The most convenient way of contacting the ore with the process gas is the moving bed principle with ascending gas flow. The ground ore has previously been pelletized with waste liquor from a later stage of the process as a binder.

The sulphates formed are eluted with water in counter-current percolator batteries. For maximum yield of uranium the first percolator must be kept at 50° C. At the same time most of the Na_2SO_4, the dominant product, is removed. In a subsequent cold and dilute compartment the rare earth metals and thorium are dissolved.

The extracted material may have the following composition expressed as milligrammes of metal for each gramme of ore:

Na	38.0
K	2.9
Al	6.3

Fe	2.6
RE	7.7
Mn	1.1
Zn	2.5
Th	0.5
U	0.25

The uranium-pregnant liquor is cooled to 5° C, whereupon $Na_2SO_4 \cdot 10\,H_2O$ is crystallized. The crystals are washed and processed into anhydrous Na_2SO_4. The supernatant liquid, which contains about 2 g/l of uranium, is stripped by solvent extraction with trilaurylamine or similar extractants. The waste liquor is used for binding of fresh pellets, whereby the cycle is closed and SO_3 from aluminium and ferric sulphates is re-used.

SUMMARY

The uranium-thorium deposit at Kvanefjeld is located in the north-western part of the Ilímaussaq alkaline intrusion, South Greenland. This intrusion is made up mainly of peralkaline, agpaitic nepheline syenites.

Four areas of uranium mineralizations are distinguished:

1. The mine area at Kvanefjeld is located in a region where remnants of the roof of the intrusion overlie lujavritic rocks. The roof rocks made up of basaltic lavas, gabbroic sills and various dyke rocks are strongly deformed and recrystallized in contact with the lujavrites. The altered volcanic rocks are injected by sheets of fine-grained lujavrite along shear zones. This mixed complex is folded and strongly mineralized in contact with sheet like intrusive bodies of a medium- to coarse-grained lujavrite. These contact zones, which may be intensely veined by analcime veinlets, represent the highest concentrations of uranium and thorium. The ore of the mine area is made up of sheets and masses of medium- to coarse-grained lujavrite and of a strongly altered complex of volcanic rocks injected by fine-grained lujavrite. The radioactive minerals are steenstrupine, a uranium-rich variety of monazite, thorite and pigmentary material. Whole rock radioelement contents of the uranium ore vary from 100 to 3 000 ppm U and 300–15 000 ppm Th. The calculation of the tonnage of ore in the mine area is based on detailed geological mapping and radiometric surveying combined with extensive laboratory work on surface samples and 43 drill holes including continuous gamma spectrometric scanning of 3500 m drill core. The resonably assured ore is calculated to be 18.6 million metric tons of ore with 5 800 metric tons of uranium, the ore grade is 310 ppm U. The estimated additional ore reserve comprises 29.4 million tons of ore with 8 700 tons uranium, the ore grade being 292 ppm U.
2. In the northernmost part of the Kvanefjeld plateau a series of fine-grained

lujavrites is intruded by veins and sheets of medium- to coarse-grained lujavrite. There are only two drill holes in this ore body. It is estimated that a 70 m thick zone contains 1200 metric tons of uranium in 3.5 million tons of ore having a grade of 350 ppm U.

3. Narrow zones of strongly deformed rocks in the north-eastern part of the Kvanefjeld plateau are locally strongly enriched in uranium and thorium. These rocks contain up to 1000 ppm U. The depth of this mineralization is unknovn.

4. The fine-grained lujavrites which are generally enriched in uranium and thorium in all parts of the intrusion, and also at Kvanefjeld, having 117 to 1200 ppm U and 63 to 5500 ppm Th. These rocks make up a considerable potential resource but are not considered in this paper.

The tonnage calculation has only been carried out for uranium. A rough estimate of the amount of thorium is obtained by multiplying the figure for the uranium ore by 2.6 which is the average Th/U ratio.

The uranium mineralization is accompanied by concentrations of a number of rare elements. In the rock body confined by the drill holes of the mine area it is estimated that hydrothermal pyrochlore-bearing analcime veins contain 1600 metric tons of Nb_2O_5 or more and that sheared volcanic rocks immediately outside the uranium-mineralized rocks contain 5 000 tons Nb_2O_5 in epistolite-murmanite-bearing rock having 0.1 % Nb_2O_5 or more. It is estimated that within the radioactive ore body there is about 21 000 tons of villiaumite (NaF), corresponding to 10 000 tons of fluorine, in rocks having more than 0.5 % NaF.

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GRØNLANDS GEOLOGISKE UNDERSØGELSE

THE GEOLOGICAL SURVEY OF GREENLAND

PLATE 1