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CONTRIBUTIONS TO
THE MINERALOGY OF ILÍMAUSSAQ
Nos 20–21

KØBENHAVN

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- 20 On the mineralogy and paragenesis of tugtupite $\text{Na}_3\text{Al}_2\text{Be}_2\text{Si}_8\text{O}_{24}(\text{Cl},\text{S})_2$ from the Ilimaussaq alkaline intrusion, South Greenland..... H. SØRENSEN, M. DANØ and O. V. PETERSEN.
- 21 The colour and luminescence of tugtupite (beryllosodalite) from Ilimaussaq, South Greenland..... A. S. POVARENNYKH, A. N. PLATONOV, A. N. TARASHCHAN and V. P. BELICHENKO.

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GRØNLANDS GEOLOGISKE UNDERSØGELSE
BULLETIN No. 95^I

ON THE MINERALOGY
AND PARAGENESIS OF TUGTUPITE
 $\text{Na}_8\text{Al}_2\text{Be}_2\text{Si}_8\text{O}_{24} (\text{Cl}, \text{S})_2$
FROM THE ILÍMAUSSAQ ALKALINE INTRUSION,
SOUTH GREENLAND

BY
HENNING SØRENSEN, MARIANNE DANØ
AND
OLE V. PETERSEN

CONTRIBUTION TO THE MINERALOGY OF ILÍMAUSSAQ No. 20

WITH 14 FIGURES AND 6 TABLES IN THE TEXT,
AND 9 PLATES

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Abstract

Tugtupite, $\text{Na}_8\text{Al}_2\text{Be}_2\text{Si}_8\text{O}_{24}(\text{Cl,S})_2$, is colourless to red, tetragonal, pseudocubic and forms triplet twins on $\{101\}$. $c:a = 1.0269 \pm 0.0003$, $d = 2.33 \text{ g/cm}^3$. $n_g = 1.499 \pm 0.001$, $n_w = 1.495 \pm 0.001$. $a_0 = 8.637 - 8.643$, $c_0 = 8.867 - 8.870$, $V_0 = 662 \text{ \AA}^3$. The description of the crystal structure is taken from DANØ (1966). The mineral occurs in hydrothermal veins in the Ilimaussaq alkaline intrusion, South Greenland, and in the Lovozero alkaline intrusion, Kola Peninsula (beryllosodalite). A number of occurrences of tugtupite in Ilimaussaq are described.

Tugtupite is most commonly associated with albite, analcime and Li-mica and is generally secondary after chkalovite. The paragenesis and origin of the mineral and a number of associated beryllium silicates are discussed.

CONTENTS

	Page
Introduction	5
Mineralogy	6
General description	6
Optical properties.....	8
X-ray diffraction	10
Chemistry	13
Differential thermal analysis and thermogravimetric analysis.....	14
Luminescence and colour.....	14
Mode of occurrence	15
1. Tugtup agtakôrfa	16
2. The head of Kangerdluarssuk	21
3. Qeqertaussaq	24
4. The Kvanefjeld area	25
5. The Taseq plateau	29
The tugtupite of Lovozero	31
Discussion	31
Paragenesis	33
References	37

INTRODUCTION

A new mineral discovered in 1957 by one of the authors (H. S.) in the coastal cliffs of Tugtup agtakôrfia on the north coast of the Tunugdliarfik fjord was described under the provisional name of "beryllium sodalite" in the reports of the International Geological Congress, Norden (SØRENSEN, 1960). Additional data were published in the discussion volume of the congress (SØRENSEN, 1963) and it was suggested that the new mineral should be named tugtupite. This is derived from the locality in which the mineral was found first.

Coinciding with the presentation of the new mineral from South Greenland a description of apparently the same mineral was published by SEMENOV & BYKOVA (1960) on material from the Lovozero intrusion in the Kola Peninsula. It was demonstrated that the mineral from Lovozero is related to sodalite but that the crystal symmetry is not cubic.

In 1965 The I.M.A. Commission on New Minerals and Mineral Names approved the name tugtupite for the new mineral since the chemical and physical properties of the mineral are distinctly different from those of sodalite.

In 1966 M. DANØ described the crystal structure of tugtupite and demonstrated that the crystals are tetragonal with the space group $I\bar{4}$ (DANØ, 1966).

Mineralogy

General description

Tugtupite is vitreous, white, pink or carmine red in hand specimen, but the colour is strongly variable. The varieties displaying strong colour preserve this colour under all conditions. The weakly coloured varieties may change colour so that they are pale or white after being kept in darkness, pink when exposed to sunshine. Strong colouration may be produced by, for instance, X-ray radiation, and this colour does not disappear when the sample is placed in darkness.

Usually the mineral forms fine-grained crystalline aggregates which may attain sizes of several centimetres. Locally tugtupite forms small crystals on the walls of cavities in massive tugtupite. The well developed crystals are short prismatic, transparent, colourless to pale pinkish, and range in size from $1 \times 1 \times 1$ mm to $3 \times 2 \times 2$ mm.

Several crystals found lining two small cavities in a sample from Tugtup agtakôrfa were measured on the two circle goniometer. Some of the matt faces could not reflect the light, and their positions were therefore determined on the universal stage. The stereogram fig. 1 gives all the faces found.

The forms developed are: $\{100\}$ matt, $\{001\}$ shiny, $\{110\}$ shiny, $\{101\}$ shiny, $\{211\}$ shiny, $\{2\bar{1}1\}$ matt and $\{1\bar{1}1\}$ matt). $\{2\bar{1}1\}$ and $\{1\bar{1}1\}$ are represented only by faces measured on the universal stage (table 1).

According to the stereogram (fig. 1) tugtupite belongs morphologically to the crystal class $\bar{4}2m$. The crystals display positive piezoelectric effect and lack a positive pyroelectric effect (DANØ, 1966, p. 813).

The axial ratio, calculated by means of the measured angles $(101):(\bar{1}01)$ and $(011):(0\bar{1}1)$, is $c:a$ 1.0269 ± 0.0003 . (Errors correspond to mean deviation from the mean value of the measured angles $(001):(\bar{1}01)$ and $(001):(0\bar{1}1)$). The ratio determined from X-ray diffraction studies is $c_0:a_0 = 1.0271 \pm 0.0002$ and 1.0260 ± 0.0002 for red tugtupite (Kvane-fjeld plateau) and white tugtupite (Taseq) respectively.

The largest crystals, which show the simplest combinations of faces, are prismatic, bounded by $\{110\}$ and $\{001\}$. The smaller crystals, which are short prismatic, show combinations of tetragonal prisms, pyramid, sphenoid and bisphenoids. Fig. 2 shows a drawing of an idealized crystal ($\{111\}$ not shown).

Fig. 1. Stereographic projection showing all the faces measured. Open circles shiny faces, black circles matt faces and concentric circles matt faces measured only on the universal stage.

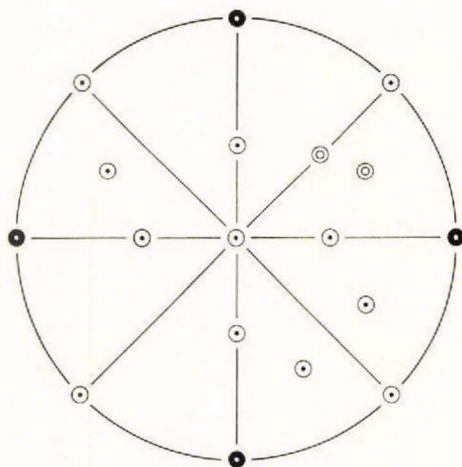


Table 1. Interfacial angles measured and calculated. The calculations are based on the axial ratio determined by direct measurement of the angles $(101):(\bar{1}01)$ and $(011):(0\bar{1}1)$

	Measured angles	Calculated angles
$(100):(010)$	$90^{\circ}00'00'' \pm 60''$	
$(100):(001)$	$90^{\circ}00'00'' \pm 60''$	
$(001):(011)$	$45^{\circ}45'38'' \pm 30''$	
$(001):(101)$		
$(001):(211)$	$66^{\circ}28'00'' \pm 60''$	$66^{\circ}28'02'' \pm 23''^*$
$(110):(211)$	$29^{\circ}36'00'' \pm 60''$	$29^{\circ}34'12'' \pm 18''$
$(101):(211)$	$30^{\circ}00'40'' \pm 60''$	$29^{\circ}59'34'' \pm 2''$

* Margin of error corresponding to the mean deviation from the mean value of the measured angles $(001):(101)$ and $(001):(011)$, assuming that the crystals are tetragonal.

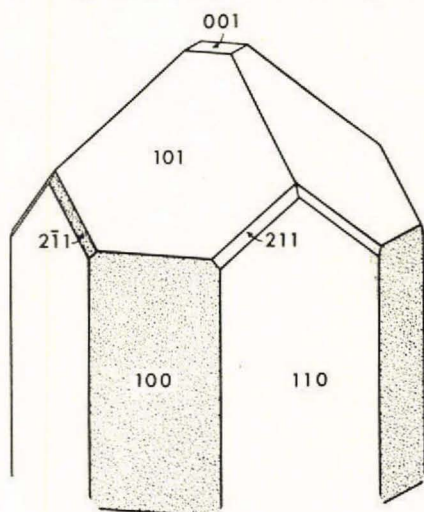


Fig. 2. Drawing of an idealized crystal of tugtupite, see the text.

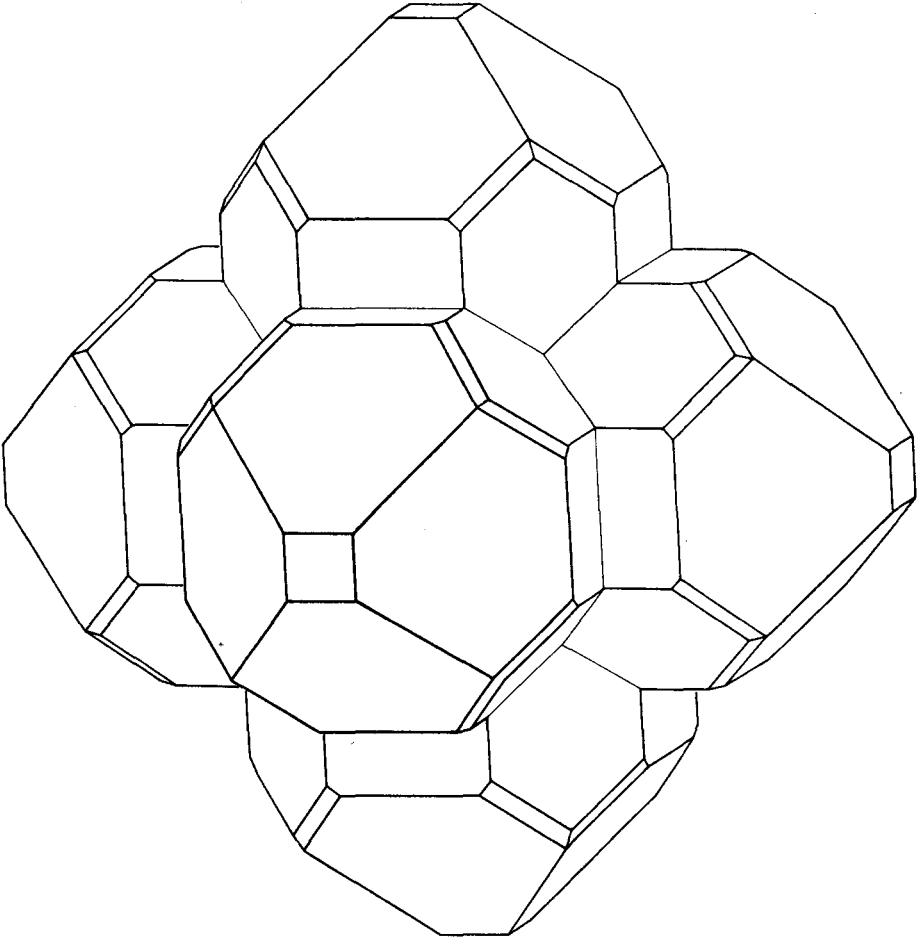


Fig. 3. Drawing of an idealized pseudocubic triplet, twin planes $\{101\}$.

The density has been determined to be 2.33 ± 0.01 g/cm³ for both red and white tugtupite. The density calculated from the chemical analysis and the unit cell volume presented in table 4 is 2.35 and 2.34 g/cm³ for red and white tugtupite respectively.

Optical properties

Under the microscope the mineral is transparent and colourless. There is a distinct cleavage parallel to $\{101\}$ and a fair cleavage parallel to $\{110\}$, corresponding to the $\{110\}$ cleavage in sodalite.

The mineral displays an intricate penetration twinning (figs 3 and 4), which in some samples is rather coarse, with the individuals attaining sizes of 1 mm. The twin plane has been measured to be (101) . In other

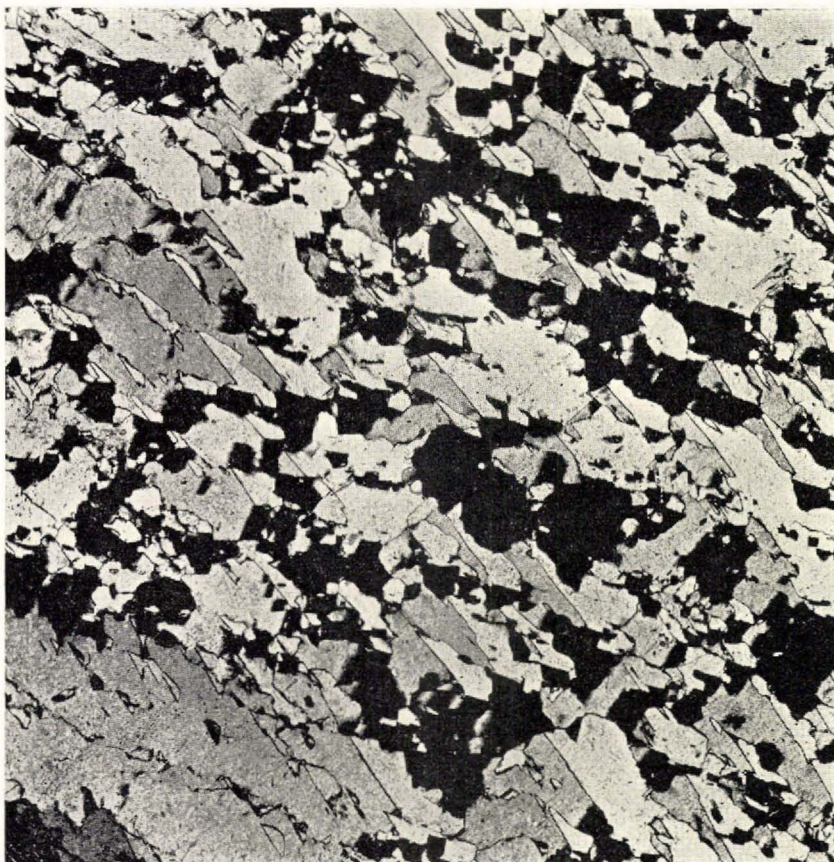


Fig. 4. Penetration triplet in tugtupite (no. 64750,1; Kvanefjeld) 17.8 x, + nic. Twin planes are {101}. The microphotograph has been taken with crossed nicols, $\lambda = 491$ nm and with addition of a phase difference of app. 440 nm to make the (001) section nearly black but the (100) and the (010) sections different. (H. MICHELSEN phot.).

samples the twinning is of a rather gritty type, the individuals being visible only at high magnification (plate 8, fig. 1). In the coarsely twinned grains the single individuals display an irregular extinction which may be a result of a submicroscopic twinning. This problem is undergoing a special study.

The mineral is optically positive and is uniaxial or has a small axial angle (up to about 10°).

The refractive indices of red and white tugtupite were measured by means of the λ -T variation method (MICHELSEN, 1957) by Mr. R. WAAGSTEIN. No measurable difference in the refractive indices n_α and n_β has been observed in the biaxial varieties.

Table 2 gives the refractive indices of a number of samples of tugtupite and of the berylliosodalite described by SEMENOV & BYKOVA (1960).

Table 2. *Refractive indices of tugtupite from three different localities in Ilímaussaq and of beryllsodalite from Lovozero*

	Red tugtupite, Kvanefjeld plateau	White tugtupi- te, Taseq slope	White tugtupi- te, Tugtup ag- takórfia (SØ- RENSEN, 1960)	Beryllsodalite, Lovozero (SEMENOV & BYKOVA, 1960)
$n_\gamma = n_\varepsilon \dots\dots\dots$	1.499 ± 0.001	1.499 ± 0.001	1.502 ± 0.002	~ 1.495
$n_\alpha = n_\beta = n_\omega \dots\dots$	1.495 ± 0.001	1.495 ± 0.001	1.496 ± 0.001	
$n_\varepsilon - n_\omega \dots\dots\dots$	0.005 ± 0.002	0.005 ± 0.002	0.006 ± 0.002	

The birefringence of the red tugtupite from the Kvanefjeld plateau seems to be slightly higher than that of the white tugtupite from the Taseq slope.

X-ray diffraction

X-ray powder diagrams of red tugtupite from the Kvanefjeld plateau and white tugtupite from the Taseq slope were taken in a Guinier-Hägg camera. Quartz was used as internal standard.

In the final calculations the reciprocal lattice constants were adapted by the least-squares method to the observed $\sin^2\theta$ values. These calculations were carried out on the GIER computer, made available to the Copenhagen Observatory by the Carlsberg Foundation. A programme (REFBASE-2) made by Mr. E. S. LEONARDSEN, head of the X-ray laboratory of the Mineralogical Institute of the University of Copenhagen, was used.

The calculated $\sin^2\theta$ values are compared with the observed values in table 3. Table 3 also presents $\sin^2\theta_{\text{obs}}$ and hkl given by DANØ (1966). The lattice constants determined from these sets of $\sin^2\theta$ values are presented in table 4. It can be seen from table 3 and table 4 that there are small but in no way significant differences between the red and the white tugtupite. In fact three other powder diagrams show that the variation inside the red and the white tugtupites is of at least the same order of magnitude.

According to DANØ (1966) tugtupite is tetragonal, space group $I\bar{4}$. The crystal structure of tugtupite is very closely related to that of sodalite. Cl is placed in the corners and the centre of the unit cell, tetrahedrally surrounded by Na. Al, Si and Be are surrounded by slightly distorted oxygen tetrahedra which share corners. The arrangement can most easily be visualized in the following way: On (or very close to) each face of the unit cell are 4 Al, Si or Be atoms, connected with oxygen to make 8-rings. Two of the oxygen atoms are above the plane, two below. The "free" O-atoms belonging to such a ring are shared with metal

Table 3. The table shows $\sin^2\theta_{\text{obs.}}$ and calc. , $^d\text{hkl}_{\text{obs.}}$ and hkl of two slightly different tugtupites (see also table 4), red and white tugtupite from the Kvanefjeld plateau and the Taseq slope respectively, and $\sin^2\theta_{\text{obs.}}$ and calc. and hkl of white-pink tugtupite from Tugtup agtakôrfa given by DANØ (1966)

Red tugtupite from the Kvanefjeld plateau					White tugtupite from the Taseq slope					White-pink tugtupite from Tugtup agtakôrfa (DANØ, 1966)			
Int.	$\sin^2\theta_{\text{obs.}}$	$\sin^2\theta_{\text{calc.}}$	$^d\text{hkl}_{\text{obs.}}$	hkl	Int.	$\sin^2\theta_{\text{obs.}}$	$\sin^2\theta_{\text{calc.}}$	$^d\text{hkl}_{\text{obs.}}$	hkl	Int.	$\sin^2\theta_{\text{obs.}}$	$\sin^2\theta_{\text{calc.}}$	hkl
7	0.01556	0.01552	6.179	101	9	0.01553	0.01551	6.187	101	s	0.0158	0.0157	101
4	0.01593	0.01593	6.107	110	5	0.01596	0.01591	6.103	110	vw	0.0162	0.0161	110
4	0.03023	0.03021	4.434	002	5	0.03028	0.03023	4.430	002	w	0.0306	0.0306	002
3	0.03190	0.03187	4.316	200	4	0.03183	0.03183	4.321	200	vvw	0.0323	0.0323	200
7	0.04615	0.04615	3.589	112	10	0.04615	0.04614	3.589	112	m	0.0467	0.0467	112
10	0.04740	0.04739	3.541	211	10	0.04740	0.04734	3.541	211	vs	0.0480	0.0480	211
										vvw?	0.0630	0.0628	202
2	0.06387	0.07374	3.050	220	2	0.06377	0.06365	3.053	120	vvw	0.0647	0.0645	220
4	0.07598	0.07594	2.797	103	4	0.07600	0.07598	2.796	103	vw	0.0770	0.0769	103
4	0.07923	0.07926	2.739	301	5	0.07938*	0.07916	2.736	301	vw	0.0803	0.0802	301
3	0.07965	0.07967	2.732	310						vvw	0.0808	0.0807	310
5	0.09390	0.09395	2.516	222	7	0.09391	0.09388	2.516	222	m	0.0952	0.0951	222
4	0.10789	0.10781	2.347	213	5	0.10782	0.10780	2.348	213	w	0.1093	0.1091	213
4	0.10986	0.10988	2.326	312	4	0.10981	0.10979	2.326	312	w	0.1113	0.1112	312
4	0.11105	0.11112	2.313	321	5	0.11097	0.11099	2.314	321	w	0.1126	0.1125	321
					2	0.12700*	0.12730	2.164	400?				
4	0.13684	0.13678	2.084	114	5	0.13682	0.13684	2.084	114	w	0.1384	0.1384	114
5	0.13959	0.13968	2.063	303	7	0.13957	0.13963	2.063	303	w	0.1413	0.1414	303
		0.14299		411			0.14281		411			0.1448	411
5	0.14300*		2.039		7	0.14300*		2.039		m	0.1451		
		0.14341		330			0.14321		330			0.1452	330
3	0.15758	0.15768	1.942	402	4	0.15754	0.15753	1.942	402	vw	0.1595	0.1596	402
										vvw	0.1612	0.1613	420

(continued)

Table 3 (cont.)

Red tugtupite from the Kvanefjeld plateau					White tugtupite from the Taseq slope					White-pink tugtupite from Tugtup agtakôrfa (DANØ, 1966)			
Int.	$\sin^2\theta_{\text{obs.}}$	$\sin^2\theta_{\text{calc.}}$	$d_{\text{hkl}_{\text{obs.}}}$	hkl	Int.	$\sin^2\theta_{\text{obs.}}$	$\sin^2\theta_{\text{calc.}}$	$d_{\text{hkl}_{\text{obs.}}}$	hkl	Int.	$\sin^2\theta_{\text{obs.}}$	$\sin^2\theta_{\text{calc.}}$	hkl
3	0.17136	0.17155	1.862	323	4	0.17134	0.17145	1.862	323	vw	0.1738	0.1737	323
2	0.18451	0.18458	1.795	224	3	0.18454	0.18458	1.795	224	vwv	0.1868	0.1869	224
3	0.18922	0.18955	1.772	422	4	0.18941	0.18935	1.771	422	vw	0.1918	0.1919	422
					2	0.20066	0.20049	1.721	314	vwv?	0.2026	0.2030	314
		0.20673		501	2	0.20332	0.20327	1.710	413	vw	0.2062	0.2059	413
4	0.20656*		1.696	431			0.20646		501				
		0.20673		431	5	0.20659*		1.696		w	0.2093	0.2093	431
					2	0.22875	0.22873	1.612	215	vwv	0.2314	0.2315	215
											0.2403		512
					3	0.23811	0.23828	1.580	521	vwv?	0.2410		521
4	0.24823	0.24832	1.547	404	5	0.24822	0.24822	1.547	404			0.2416	
2	0.25510	0.25495	1.526	440	4	0.25458	0.25459	1.528	440				
		0.26715		503	3	0.26050	0.26055	1.510	305				
3	0.26715*		1.491	433			0.26692		503				
		0.26715		433	4	0.26693*		1.492					
					1	0.27207	0.27209	1.478	006				
3	0.28018	0.28019	1.456	424	4	0.28003	0.28005	1.457	424				
3	0.28526	0.28516	1.443	442	4	0.28479	0.28482	1.445	442				
1	0.28678	0.28681	1.439	600									
3	0.29255	0.29239	1.425	325	4	0.29236	0.29238	1.426	325				
3	0.29919	0.29902	1.409	523	4	0.29880	0.29875	1.410	535				
3	0.30100	0.30109	1.405	532		0.30081	0.30074	1.406	532				

* Values which enter into the final calculations with the weight 0.0.

Table 4. *Unit cell parameters of red tugtupite from the Kvanefjeld plateau, white tugtupite from the Taseq slope, and white-pink tugtupite from Tugtup agtakôrfa (DANØ, 1966)*

	Red tugtupite, Kvanefjeld plateau	White tugtupite, Taseq slope	White-pink tugtupite, Tugtup agtakôrfa (DANØ, 1966)
a_0	$8.637 \pm 0.001 \text{ \AA}$	$8.643 \pm 0.001 \text{ \AA}$	$8.583 \pm 0.004 \text{ \AA}$
c_0	$8.870 \pm 0.002 \text{ \AA}$	$8.867 \pm 0.001 \text{ \AA}$	$8.817 \pm 0.004 \text{ \AA}$
$c_0 : a_0$	1.0271 ± 0.0002	1.0260 ± 0.0002	1.0273 ± 0.0006
vol.	662 \AA^3	662 \AA^3	658 \AA^3

atoms of an 8-ring on another face. In holes between the rings there are Cl atoms with 4 Na around them. In tugtupite the rings on (001) are pure Si-O rings while the rings on (100) and (010) have 1 Be, 1 Al and 2 Si alternating in agreement with the tetragonal symmetry. There is thus an ordering of Si, Al and Be, as was suggested by SEMENOV & BYKOVA (1960).

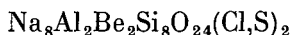
The following bond lengths were determined by DANØ (1966).

$$\begin{aligned} \text{Be} - \text{O} &= 1.608 \pm 0.012 \text{ \AA} \\ \text{Al} - \text{O} &= 1.762 \pm 0.014 \text{ \AA} \\ \text{Si} - \text{O} &= 1.601 \pm 0.008 \text{ \AA} \end{aligned}$$

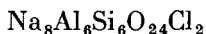
Chemistry

The chemical analyses of tugtupite from Ilímaussaq and Lovozero are reproduced in table 5. Apart from the high content of water in the sample from Lovozero the two analyses are practically identical, although the Lovozero sample is richer in Al_2O_3 and poorer in SiO_2 , Na_2O and Cl than the sample analysed from Ilímaussaq.

The formula of the mineral is calculated as



which when compared with the formula of sodalite



indicates that there is a substitution of BeSi for AlAl in the sodalite structure. This accounts for the lower symmetry of the tugtupite.

Table 5. *Chemical analysis of tugtupite from Ilimaussaq, metal atoms in 100 g as presented by DANØ (1966), and chemical analysis of beryll-sodalite as presented by SEMENOV & BYKOVA (1960).*

	Tugtupite from Ilimaussaq		Beryllsodalite from Lovozero
	Weight percent	Metal atoms in 100 g	Weight percent
SiO ₂	51.58	0.861	50.45
Al ₂ O ₃	11.15	0.219	12.56
Fe ₂ O ₃	tr		
Ga ₂ O ₃	(0.035)*		0.043
BeO	5.40	0.216	5.30
MgO	0.20	0.005	—
CaO	—		0.50
Na ₂ O	25.52	0.822	23.26
K ₂ O	0.12	0.002	0.40
H ₂ O ⁺			1.50
H ₂ O ⁻	0.03		1.51
S	0.33	0.010	
Cl	7.28	0.205	6.04
-O = Cl ₂ , S	1.80		1.40
Total	99.81		100.16
Analyst	ME MOURITZEN		A. V. BYKOVA

* Determined in the laboratories of IMGRE, Moscow.

Differential thermal analysis and thermogravimetric analysis

The differential thermal analysis of red tugtupite from the Kvane-fjeld plateau shows a weak exothermal reaction at about 190°C (peak temperature about 240°) and a distinct endothermal reaction at about 990°C (peak temperature about 1040°C), the latter corresponding to the melting of the mineral.

According to DANØ (1966, p. 813) X-ray powder diagrams showed no change in symmetry when the mineral was heated to the melting point.

The thermogravimetric analysis of red tugtupite indicates a loss of Cl and S, starting at about 890°C and continuing up to at least about 1020°C.

Luminescence and colour

POVARENNYKH, PLATOV, TARASHCHAN & BELICHENKO (in press) have examined the visible region of the spectral absorption curves and

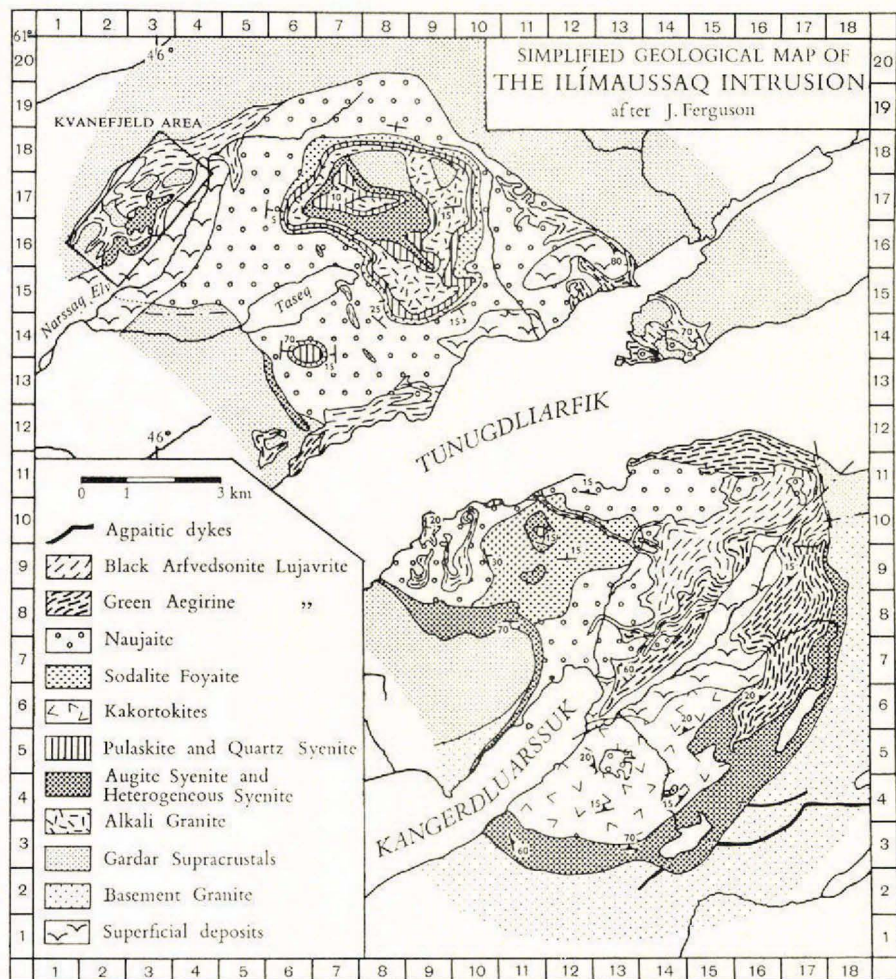


Fig. 5. Geological map of the Ilímaussaq intrusion after FERGUSON (1964). The coordinates of the localities are: Tugtup agtakôrflia 8,12; Head of Kangerdluarsuk 12,7; Kvanefjeld 3,16; Taseq region 5,15.

the luminescence spectrum of tugtupite from Ilímaussaq. It is suggested that the luminescence is caused by S_2^- molecular ions occupying the position of the Cl ions in the crystal structure. These ions are also responsible for the colour of the mineral, but other, thermally less stable, radiation centres may also play a role.

Mode of occurrence

Tugtupite has been found in many places all over the Ilímaussaq intrusion (fig. 5). The mineral is confined to hydrothermal veins inter-

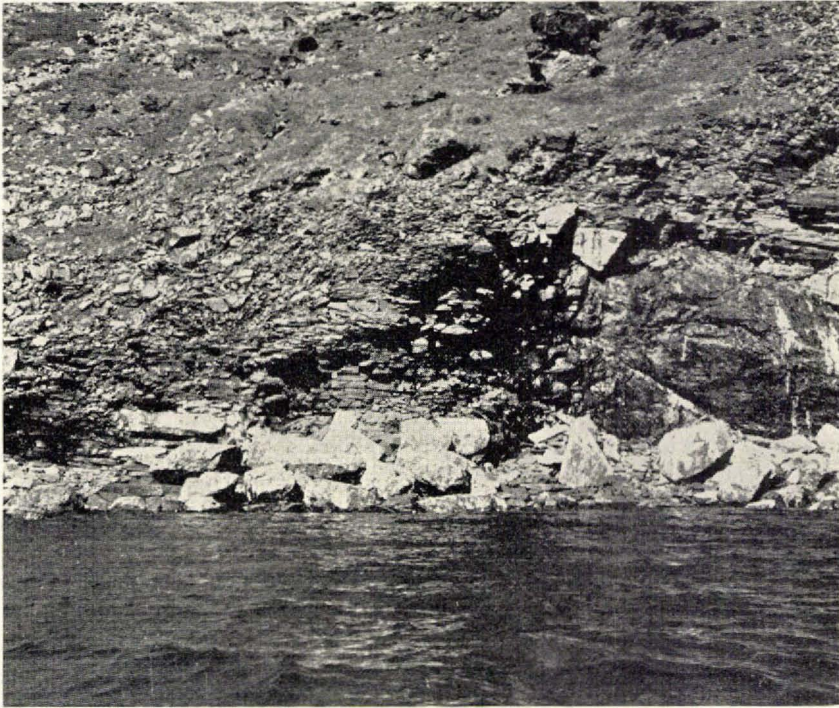


Fig. 6. Tugtup agtakôrfia. Inclusions of naujaite (white) in laminated and schistose lujavrite.

secting poikilitic sodalite syenite (naujaite) and syenite. The mode of occurrence has been studied in a number of localities, namely Tugtup agtakôrfia, the head of Kangerdluarssuk, Qeqertaussaq, Kvanefjeld and the Taseq plateau.

1. Tugtup agtakôrfia

Tugtup agtakôrfia, a small point on the north coast of the Tunugdliarfik fjord, is the type locality of tugtupite.

The point is made up of black lujavrite with big inclusions of naujaite (fig. 6). Tugtupite occurs as a granular mass in a vein of albitite, 30–50 cm thick and practically vertical, intersecting one of the bodies of naujaite (SØRENSEN, 1960 and 1962). The vein does not intersect the lujavrite overlying (and enclosing) this body of naujaite (figs 7 and 8).

Albite is the predominant mineral of the major part of the vein. It is either sugary or cleavelanditic. In the latter case the laths are set at right angles to the vertical contacts. In cavities there are small tabular crystals of albite.



Fig. 7. Two vertical veins of albitite (centre and centre right) in naujaite enclosed in lujavrite. Tugtup agtakörfia. The tugtupite locality is found in the uppermost part of the left vein (see also fig. 8). The dark rims are of acmite + steenstrupine.

Scattered through the granular albitite are grey patches of microcline which are partially replaced by albitite. Accessories are epistilite, yellow sodalite, Li-mica, schizolite, steenstrupine, sphalerite, acmite and arfvedsonite, all of which may occur in large concentrations around patches of analcime. The borders of the vein are enriched in acmite and steenstrupine. Ussingite and tetragonal natrolite have been found in one sample of the border zone (ANDERSEN, DANØ & PETERSEN, 1969).

The uppermost part of the vein is made up of brown masses up to 20 cm across of analcime which display a distinct cubic cleavage. There are also aggregates of white, brown or transparent icositetrahedra of analcime up to 1 cm across, often in vugs. In the analcime there are small "screens" of white albitite. Yellow sodalite, sphalerite and prismatic crystals of schizolite are found in the cavities partially filled with crystals of analcime. These crystals have white films of tetragonal natrolite. Tugtupite is confined to the lowermost part of this analcime rock, and is found about 70 cm below the upper contact of the vein (figs 8, 9 and 10).



Fig. 8. Tugtupite-bearing part of albitite vein at Tugtup agtakôrfa. Hammer handle about 40 cm long. The lujavrite in the left foreground is not in place but consists of boulders.

This almost pure analcime rock is underlain by albitite with scattered analcime and is separated from the overlying lujavrite by a black zone of arfvedsonite, 1 cm thick.

The uppermost part of the analcime rock is clearly formed at the expense of naujaite since it contains corroded and altered remnants of naujaitic sodalite, microcline and eudialyte. The poikilitic structure is well preserved.

This analcime-rich part of the vein has inclusions of acmite and steenstrupine near the contact with the naujaite, indicating that the acmite-steenstrupine marginal zone of the albitite has been partially replaced by the analcime.

Tugtupite forms an irregular, fine-grained mass up to 40 cm across, which appears to send a network of thin veinlets into the adjacent

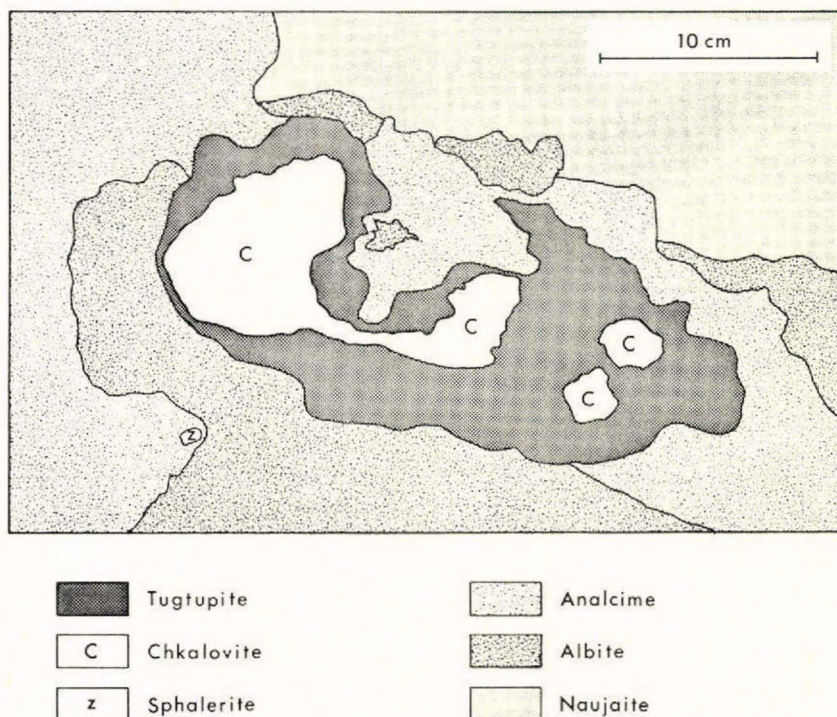


Fig. 9. Close-up of the tugtupite-chkalovite intergrowth at Tugtup agtakôrfa.

analcime-albite rock. The tugtupite contains large masses of chkalovite up to 10 cm across, and there are also scattered areas of analcime, often in the form of discrete crystals. The chkalovite is intersected by veinlets of fine-grained tugtupite. These veinlets, which may be only a millimetre thick, swell to thicknesses of several centimetres, in which cases there often are cavities containing small crystals of tugtupite.

Under the microscope (sample nos. 21059 A and B) it can be seen that the grains of chkalovite enclosed in tugtupite are deformed (undulatory extinction) and are intersected by zones of crushing in which the chkalovite forms small rounded grains. These zones are partially replaced by tugtupite (plate 1, fig. 2).

The chkalovite is generally enclosed in the tugtupite, but scattered grains of chkalovite have been found in analcime-rich areas in albitite (sample nos. B 1 and B 3). The age relation between chkalovite and albite is difficult to determine. Inclusions of albite of corroded appearance and of microcline and analcime in the chkalovite may be due to a "thin section effect" since the grains of chkalovite enclosed in albite are of amoeboid outline. The chkalovite is in places in direct contact with albite

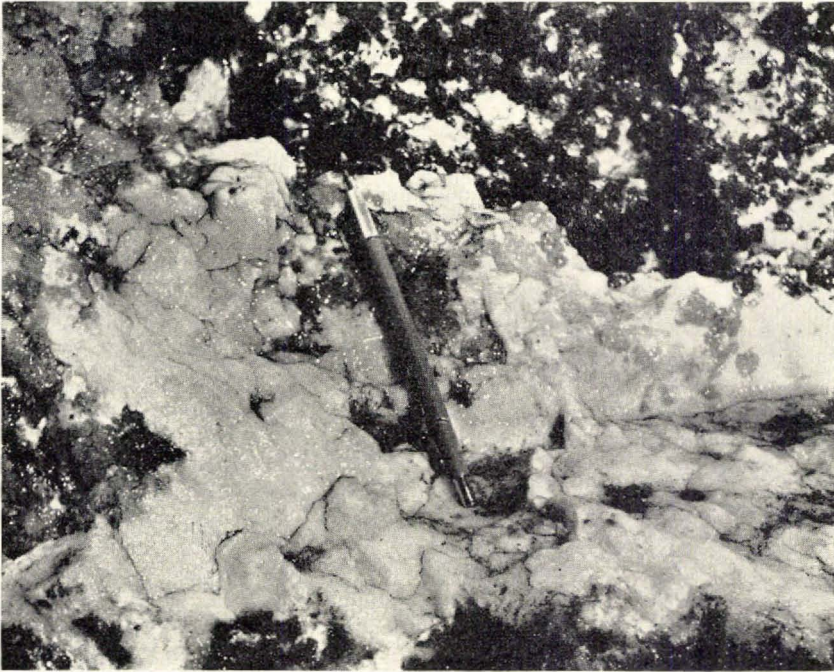


Fig. 10. Same as fig. 9. The pencil (16 cm long) is placed on the tugtupite-chkalovite. The white mineral is albite, the grey is analcime (note crystals to the left), the black (top and bottom) is acmite-steenstrupine margin of vein.

while in other places it is separated from that mineral by granular masses of tugtupite. Chkalovite appears to be corroded by analcime, which may contain inclusions of albite.

The areas of analcime in the albitite adjacent to the tugtupite-rich area contain corroded grains of albite and appear to be formed later than the albitite. The analcime areas are surrounded by a branching network of thin veinlets of analcime and natrolite which penetrate into the albitite. There may be patches of tugtupite along the margins of the "geodes" of analcime.

Tugtupite occurs as granular masses in which the grain size varies from 0.5 mm in the thin veinlets to about 1 mm in the thicker masses with gradual transitions. The tugtupite grains are generally of irregular outline and thus display an interlocking type of intergrowth (plate 2, fig. 1).

The tugtupite contains aggregates of small flakes of Li-mica, and there are inclusions of chkalovite, albite, microcline (plate 2, fig. 2), sodalite, analcime, epistolite, schizolite, arfvedsonite, sphalerite, aegirine-acmite and steenstrupine.

The veinlets of tugtupite intersect not only the chkalovite but penetrate into the albite and microcline of the enclosing albitite. The twin lamellae of the albite are intersected by these veins.

The relations between tugtupite and analcime are less clear. The two minerals have straight or faintly lobate mutual boundaries. There are inclusions of analcime in the tugtupite, and tugtupite crystals are found in interstices between analcime crystals, favouring the view that tugtupite is later than analcime.

When considering the age relations of the minerals it should be mentioned that the chkalovite enclosed in tugtupite often shows signs of deformation, while that enclosed in albite is undeformed. The laths of albite are also undeformed.

2. The head of Kangerdluarssuk

DANØ & SØRENSEN (1959, fig. 3) and SØRENSEN (1962, p. 28 and p. 114) have described a one metre thick vertical vein intersecting crumbling naujaite near Lilleelv at the head of the fjord. The vein is composed of fine-grained aegirine and albite with minor amounts of analcime, sodalite and natrolite.

Patches of the vein are composed of crystals of aegirine and steenstrupine up to 1 cm or more across in a fine-grained groundmass of albite, microcline, ussingite, aegirine needles, sodalite, analcime and natrolite. Accessories are lovozerite, sphalerite, galena, chkalovite, tugtupite, Li-mica, igdloite, britholite, schizolite and, along the margins of the vein, eucolite.

The coarse-grained patches have been studied in sample nos. 18468 and 21149. The ussingite clearly replaces microcline. Fractures in the eucolite and the interstices between the aegirine crystals are mainly occupied by ussingite and, to a lesser extent, by Li-mica, albite and microcline. As albite is predominant around the eucolite and aegirine grains, this may indicate that the ussingite was formed earlier than the albite. This is difficult to establish in the matrix because albite and ussingite have interlocking boundaries.

Large grains of sodalite are set in a fine-grained groundmass of albite, aegirine, steenstrupine and lovozerite, and they are penetrated by ussingite and albite.

Chkalovite occurs as large and small grains with rounded or irregular outlines. They are generally surrounded by thin zones of fine-grained tugtupite, although chkalovite has been observed in direct contact with albite, ussingite and microcline. There is most often a rim of fine-grained albite between the tugtupite-chkalovite and the ussingite. The zone of tugtupite is thicker at these places than where the albite rim is lacking.

Chkalovite borders on eucolite and aegirine and is penetrated by prismatic crystals of schizolite. The tugtupite rims contain inclusions of eucolite, aegirine, microcline, albite, sphalerite (partly altered into hemimorphite), lovozerite, steenstrupine, Li-mica and britholite. Small needles of aegirine are orientated as in the adjacent green rock.

A few metres to the west of the above-mentioned vein, in the gravel covering the crumbling naujaite, there is a train of boulders of albitite. Even if polygonal structures (patterned ground) with cross sections up to two metres are well developed in this gravel, the train of albitite boulders has been traced with very few interruptions and practically without displacement for more than 100 m.

The vein appears to be about 20 cm thick and is mainly made up of albite, sugary as well as cleavelanditic.

In the marginal part of the vein and in the adjacent naujaite there are large masses of yellow sodalite which contain corroded remnants of naujaitic minerals and thus partly replace that rock. This sodalite is intersected by veins of felt-like aegirine branching out from a dense green rock which occurs between the sodalite and the albitite of the central part of the vein. The sodalite is also cut by thin veins of albite with varying, sometimes high, contents of microcline in the cores. These veins occupy cleavage fractures in the sodalite (plate 3, fig. 4).

The marginal dense green rock is composed of interlocking fibres of aegirine with interstitial arfvedsonite, albite and igdloite. This rock is partly replaced by albite and is cut by veinlets of albite from the central part of the vein.

The partly replaced dense green rock was studied in thin section nos. 66131, 66132, 66134 and 66135. In addition to aggregates of irregularly shaped grains of albite and numerous needles of aegirine, which are sometimes bent, there are scattered laths of microcline and amoeboid areas of analcime up to 0.5 cm across. The latter may have cores of sodalite (plate 3, fig. 2). The analcime in places forms a very irregular interstitial network in the albitite. This albite-analcime rock contains scattered grains of chkalovite which have rounded, strongly corroded outlines. They are enclosed in albite-analcime; there are spots of very fine-grained tugtupite (?) along their margins.

This marginal part of the vein furthermore contains steenstrupine, lovozerite, epistolite, Li-mica, schizolite, britholite and pseudomorphs after eudialyte. It is cut by veinlets of natrolite and tugtupite (?).

The contact relations between the marginal fine-grained albite-analcime rock and the cleavelanditic albite of the central part of the vein are difficult to establish. There may either be an interfingering of the two rocks across the contact, or the cleavelanditic albitite may pass

into the fine-grained albite-analcime rock. There is no analcime in the cleavelandite. The analcime of the adjacent fine-grained albite-analcime rock forms elongated areas which are arranged parallel to the contact (plate 4, fig. 1).

The albite laths of the cleavelanditic albitite are "foliaceous" (cf. VLASOV, KUZMENKO & ESKOVA, 1959, p. 189) and are generally oriented at right angles to the contact, except in the marginal, fine-grained parts. There are inclusions of aegirine felt, scattered Li-mica and cavities with flat crystals of albite. The albite is intersected by white veins of natrolite and by veins of light pink tugtupite. The latter generally have a wavy course.

The veinlets of tugtupite (no. 66133) are generally bounded by flakes of Li-mica, often bent, small and large flakes occurring together (plate 4, fig. 2). In the Li-mica there are small flakes of epistolite, a little neptunite and small grains of a monazite-like mineral. There are patches of tugtupite in the Li-mica. The tugtupite of the veinlets forms fine-grained masses of equigranular grains which are less than 0.1 mm across. There are rare interstitial grains of albite.

The veinlets branch out from larger aggregates of granular tugtupite with a grain size of 0.1 to 3 mm. In these masses there are curved flakes of Li-mica and small interstitial grains of albite. Many of the tugtupite grains have wavy extinction, and the gritty type of twinning is widespread.

In the border between naujaite and albite there is in places a rather coarse-grained albitite composed of laths of albite a few mm long which are intergrown in such a way that there are numerous interstitial pore holes. The albitite appears to pass into the more massive cleavelanditic albitite in which the albite laths are in parallel orientation. The porous albitite partly replaces a rock rich in eudialyte and aegirine prisms and partly the marginal aegirine-rich border zone of the veins. It contains patches of tugtupite.

This type of albitite was examined in thin sections of sample nos. B.2 and 66135. The albite laths have few twin lamellae and foliaceous outlines. The albitite is intersected by numerous veinlets of very fine-grained natrolite which cut across the albite grains or are situated along their cleavages and along grain boundaries. The veinlets are up to 0.2 mm wide (plate 5, fig. 1).

The areas of tugtupite, which are made up of small grains of tugtupite of fairly polygonal outlines, are not intersected by the natrolite veinlets and thus appear to have formed later than these. Short apophyses of tugtupite occupy interstitial areas in the albite adjacent to the masses of tugtupite. They may occupy the central parts of natrolite veinlets. There are scattered inclusions of albite in the marginal parts

of the tugtupite aggregates. There are no large flakes of Li-mica in association with this type of tugtupite.

The largest masses of tugtupite, up to several centimetres across, are associated with light yellow sodalite. These masses often display hexagonal outlines and may be up to 20 cm across. Sodalite generally forms the margins of these areas while tugtupite occurs in the central parts. The tugtupite aggregates are scattered in an irregular way over the sodalite and often have thin marginal rims of fine-grained Li-mica. There are also irregular patches of albitite and ussingite in the sodalite, and there are small cavities lined by crystals of tugtupite.

The sodalite appears to be enclosed in albite and also borders on the aegirine rock of the vein margin. The albite is partly cleavelanditic, partly sugary. It has intergranular fine-grained natrolite and is intersected by veinlets of Li-mica.

Ussingite forms large aggregates which are penetrated by a fine network of natrolite veinlets up to 0.2 mm wide. The natrolite veinlets do not intersect the albite laths, indicating that the albite was formed later than the ussingite and natrolite (plate 5, fig. 2). The ussingite contains inclusion of aegirine, sodalite, schizolite, igdloite, epistolite and sphalerite.

The tugtupite of this association was examined in thin sections of specimen nos. 64901 and 77227. The aggregates of tugtupite consist of equidimensional grains with straight or irregular mutual boundaries. The grains often show wavy extinction. The individual grains may be up to 5 mm across. There are scattered inclusions of aegirine, Li-mica, albite, granulated sodalite and ussingite. The enclosed ussingite is intersected by veinlets of fine-grained natrolite. The inclusions in the tugtupite areas generally occupy interstitial positions. Along the margins of the tugtupite aggregates there are often thin zones composed of sodalite (plate 5, fig. 2) or of numerous small flakes of Li-mica (plate 6, fig. 1) with cloudy plates of epistolite. The latter mineral is partially replaced by a fine-grained aggregate possibly consisting of gerassimovskite.

3. Qeqertaussaq

On the small island of Qeqertaussaq there is a number of late veins (SØRENSEN, 1962, p. 22 and p. 100). Thin veins of felt-like aegirine and black lujavrite are partly replaced by albite.

In the albititic parts of these veins there are grains up to 0.3 cm large of chkalovite surrounded by amoeboid zones of tugtupite with a very intricate penetration twinning of the gritty type.

Accessories in the veins are microcline, arfvedsonite, astrophylite, sphalerite, schizolite, britholite, monazite, steenstrupine and epistolite. Analcime and natrolite are present in small amounts.



Fig. 11. Excavation in tugtupite-bearing vein at Kvanefjeld. Photo taken in July, 1969.

4. The Kvanefjeld area

In the northernmost part of the Ilmaussaq intrusion tugtupite has been observed in a number of places, especially on the Kvanefjeld plateau, but also on the north wall of the Gletscherelv valley below the plateau. This slope in its lower part is made up of naujaite enclosed in and penetrated by lujavrite. In its upper part augite syenite and anorthosite are intersected by lujavrite veins containing small xenoliths of naujaite (cf. SØRENSEN, HANSEN & BONDESEN, 1969).

Tugtupite has been found in scattered veins in naujaite and augite syenite, often in spatial association with arfvedsonite lujavrite. These veins are up to 50 cm wide and have been traced for up to 50 m. The width of the generally vertical veins varies along their strike. They often stop abruptly, even where empty joints are continuous with the veins (figs 11, 12, 13 and 14).

These veins are mainly composed of fine-grained albite or coarse-grained analcime. They may be zoned, having tugtupite in the central part, and often have inclusions of felt-like aegirine and of augite syenite.

The augite syenite is strongly deformed in the zones occupied by these albititic veins and may have disseminated tugtupite.

The tugtupite from these veins is the most strongly coloured variety of the mineral found in Ilmaussaq so far. The colour is an intense carmine-red. The tugtupite occurs in angular patches up to 10 cm across, often with cores of chkalovite and clearly replacing crystals of that



Fig. 12. The vein excavated in fig. 11. For explanation see fig. 13. Photo taken in July, 1968.








- | | | | |
|---|------------------------------|---|------------------|
|  | Tugtupite |  | Syenite |
|  | Pyrochlore |  | Deformed syenite |
|  | Albite, analcime, chkalovite | | |

Fig. 13. Same vein as fig. 12. Kvanefjeld.



Fig. 14. Vertical vein of albitic-analcime in augite syenite a few metres east of the vein shown in figs 11, 12, 13.

mineral. There are, moreover, inclusions of albitic, microcline, aegirine and epistolite. Tugtupite also forms branching veinlets in grains of chkalovite and in the albitic. This leaves the impression that the tugtupite impregnates the vein rock (plate 6, fig. 2).

The albitic matrix of the veins has thin streaks of pyrochlore, neptunite, igdloite and fine-grained arfvedsonite. Further constituents seen in hand specimen are yellow sodalite, natrolite and tetragonal natrolite, neptunite, schizolite, patches of pyrochlore, sphalerite, Limica, epistolite and beryllite. The streaks of pyrochlore-neptunite intersect all other constituents, including tugtupite.

The analcime-rich vein rocks are composed of equidimensional grains of analcime with grain sizes of 1 cm or more. There are scattered patches of albitic aggregates and of aggregates of microcline penetrated by albitic. The analcime appears to penetrate the albitic-microcline and may also occur as vermicular inclusions along the margins of albitic grains. There are small patches of sodalite in the analcime. Cavities are wholly or partly filled by aggregates of tetragonal natrolite, in places associated with schizolite.

Tugtupite displays lobed boundaries towards analcime. The tugtupite is intersected by zones of brown pigmentation, gelbertrandite (?) and perhaps Li-mica.

Large grains of chkalovite have marginal zones of tugtupite against the enclosing analcime (plate 7, fig. 1) and are penetrated by tugtupite along cracks (plate 7, fig. 2). Thin zones of beryllite in the chkalovite do not penetrate into the tugtupite. The tugtupite contains inclusions of analcime and may be crowded with pigmentary material, aegirine and arfvedsonite needles.

On the Kvanefjeld plateau tugtupite has also been detected in drill holes, for instance in drill hole no. 22 at a depth of 63.92 m below the surface. The tugtupite occurs in a vein in naujaite. The tugtupite is associated with crystals of light pink sorensenite up to 1 cm long, and occurs generally as marginal zones around that mineral.

Under the microscope it can be seen that the matrix of the vein is made up of laths of microcline up to 0.5 cm long. The microcline is strongly corroded by analcime and natrolite. There are small laths of albite, aggregates of fine-grained neptunite, schizolite, arfvedsonite and aegirine, scattered small crystals of monazite and a very few anhedra of steenstrupine. In the analcime there are corroded grains of nepheline, and pseudomorphs after eudialyte that are mainly composed of katapleiite. Natrolite occurs as very pigmented areas composed of thin, in part radiating needles.

Sorensenite occurs as bunches of parallel prisms which are set in a matrix of tugtupite (plate 8, fig. 1). The latter also penetrates the sorensenite along grain boundaries and irregular cracks and appears to replace that mineral. Sorensenite is not in direct contact with microcline or analcime.

Tugtupite penetrates into the adjacent microcline and encloses well developed crystals of that mineral (plate 8, fig. 1). Tugtupite has occasionally a thin zone of sodalite in contact with analcime; in other places the two minerals are in direct contact. The tugtupite contains lines of brown pigmentation (bertrandite?). In places there are small needles of natrolite (?) enclosed in the tugtupite.

Some of the veins of albitite contain chkalovite without rims of tugtupite. The albititic matrix of these veins is very heterogeneous as to grain size. The anhedra of chkalovite have lobed outlines and are altered into analcime and beryllite (and gelbertrandite?) along cracks. There may also be epididymite in these zones, but no tugtupite. The chkalovite (and its beryllite veinlets) is cut by veins of microcline (and subordinate albite). They contain scattered prisms of sorensenite and a little niobophyllite.

SEMENOV et al. (1965) have described zoned bodies from Kvanefjeld composed of marginal microcline, arfvedsonite and steenstrupine,

and of cores of analcime, sodalite and natrolite. They also contain chkalovite, sorensenite, pyrochlore and sphalerite; beryllite occupies thin fractures in the chkalovite (ANDERSEN, 1967). The sorensenite is enclosed in analcime and is partly replaced by beryllite (ANDERSEN, *op. cit.*). ANDERSEN has described an occurrence of epididymite and eudidymite enclosed in analcime. Bertrandite partly replaces these two beryllium minerals but not the sorensenite present in this sample.

5. The Taseq plateau

A number of occurrences of tugtupite has been found on the Taseq plateau and on the slope between this plateau and the Gletscherelv. A preliminary account of the results of a detailed study of this area of beryllium mineralization is in preparation (ENGELL, HANSEN, KUNZENDORF & LØVBORG). Therefore only a brief review of the known associations of tugtupite in this region will be presented here.

The beryllium-bearing veins studied so far are confined to the naujaites of the uppermost part of the intrusion. The veins are especially numerous just above regions in which veins of lujavrite intersect the naujaites.

Four main types of veins have been distinguished so far:

a) In naujaite and coarse-grained lujavrite there are zoned pegmatites containing marginal microcline, arfvedsonite and rare steenstrupine and sodalite and cores of ussingite, albite, nenadkevichite, neptunite, sphalerite and tugtupite (SEMENOV, KAZAKOVA & ALEKSANDROVA, 1967, p. 5).

b) Veins rich in ussingite have marginal zones of aegirine, yellow sodalite and steenstrupine. The cores are composed of ussingite, analcime, natrolite, epistolite, gerassimovskite, chkalovite, microcline, Li-mica, sphalerite, galena, molybdenite, chalchothallite, niobophyllite and rare tugtupite (cf. SEMENOV, SØRENSEN, BESSMERTNAJA & NOVOROSOVA, 1967).

The ussingite of the core forms fine-grained aggregates with a grain size less than 0.1 mm. There are inclusions of aegirine needles, sodalite, Li-mica, steenstrupine and schizolite.

The large grains of chkalovite enclosed in the ussingite are partially crushed and intersected by zones of granulation which are partly occupied by aggregates of ussingite, aegirine, analcime, sphalerite, schizolite, epistolite, Li-mica and steenstrupine. Tetragonal natrolite (and analcime) occurs in cavities in the ussingite (plate 8, fig. 2). There are small crystals of chabazite (?) in the natrolite.

In a few samples pink tugtupite forms narrow rims between chkalovite and ussingite and also fills fractures in these two minerals. The

tugtupite contains inclusions of chkalovite, ussingite and epistolite. Larger areas of tugtupite are intimately associated with Li-mica. There may be marginal sodalite.

Ussingite veined by natrolite is in places partially replaced by albitite which is either granular or cleavelanditic. There are generally zones of natrolite between ussingite and albite, and the albite laths may be set at right angles to the patches of ussingite. In these cases tugtupite encloses not only ussingite veined by natrolite but also albite, and there are veinlets of tugtupite in the albitite.

c) There are several varieties of albitite in this vein type. A few of these have been mentioned briefly by SEMENOV & SØRENSEN (1966). Some of the veins are coarse-grained, recalling those of Tugtup agtakôrfa and Kangerdluarssuk; others are extremely fine-grained, but having patches of more coarse-grained albite.

i. In the fine-grained albitites the matrix is composed of interlocking grains of albite less than 0.02 mm across, and there are scattered grains of microcline, larger laths of albite and a good deal of fluorite. Accessories are Li-mica, neptunite, schizolite, pseudomorphs after epistolite (?), pyrochlore, igdloite, sphalerite, aegirine, arfvedsonite, allanite and biotite.

Tugtupite occurs as centimetre-sized anheda, penetrating the matrix of albite and microcline, mainly along grain boundaries but also along cracks in the albite. There are inclusions of albite, microcline, schizolite, arfvedsonite and neptunite (plate 9, fig. 1).

Some of these veins have patches of analcime containing inclusions of albite and microcline. Tugtupite appears to be associated with the analcime and contains inclusions of that mineral.

ii. In albitites containing eudidymite and epididymite there are patches of strongly pigmented analcime and tugtupite (SEMENOV & SØRENSEN, 1966). These albitites have late genthelvite (BOLLINGBERG & PETERSEN, 1967) and leucophane.

Analcime occupies areas of irregular shape and appears to branch into the adjacent albite-microcline along grain boundaries. There are small patches of tugtupite at the ends of the veinlets.

The eudidymite and epididymite are separated from the adjoining albite and are penetrated by veinlets of analcime, tugtupite and Li-mica. Tugtupite also penetrates the albitite. The analcime and tugtupite are both strongly pigmented, and as they both display a gritty type of twinning they are difficult to distinguish from each other.

iii. In a boulder of albitite there are crystals of chkalovite up to 5 cm across and streaks of pyrochlore, neptunite and igdloite set in a matrix of coarse-grained albite. There are tabular crystals of albite in cavities.

The crystals of chkalovite have spherulite beryllite on irregular cracks and are separated from the albite by rims composed of eudidymite and epididymite. The cracks containing beryllite are cut by these rims (plate 9, fig. 2).

Between the epididymite and albite there are zones composed of gelbertrandite (?), beryllite and niobophyllite.

There is no tugtupite or analcime in this sample.

d) Tugtupite has been found in analcime veins as marginal zones around, and as thin veinlets cutting crystals of chkalovite. This tugtupite is associated with Li-mica. Analcime veinlets (with border zones of tugtupite) cut the chkalovite, and there are inclusions of analcime in the tugtupite.

Accessories in these rocks are schizolite, aegirine, neptunite, ore, steenstrupine and pyrochlore. There may be patches composed of interlocking laths of microcline with subordinate albite. The tugtupite encloses these two minerals.

The tugtupite of Lovozero

Apart from Ilímaussaq only one more locality of tugtupite (beryllosodalite) has been discovered, namely the Lovozero intrusion of the Kola Peninsula (SEMENOV & BYKOVA, 1960).

The mineral is rather rare in Lovozero. It forms masses up to 0.3 cm across in zeolite. It is cryptocrystalline in thin section and forms masses displaying a weak aggregate polarisation.

Tugtupite is secondary after chkalovite, which is usually found in masses of ussingite. The ussingite is replaced by analcime, natrolite and chabazite. Associated minerals are murmanite (the Ti-rich member of the murmanite-epistolite mineral group, in which epistolite is a Nb-rich member), aegirine II, sphalerite, schizolite, neptunite, steenstrupine, gerassimovskite, etc. (SEMENOV, ORGANOVA & KUKHARCHIK, 1961; YAKOVLEVSKAJA & SEMENOV, 1963). This shows clearly that the mode of occurrence of tugtupite (beryllosodalite) is practically identical in the two closely related agpaite intrusions, Lovozero and Ilímaussaq.

Discussion

Tugtupite in the Ilímaussaq intrusion is confined to veins dominated by albite and/or analcime. As discussed by SØRENSEN (1962), the albite-analcime veins occur in zones of fracturing and displacement in naujaite and syenite, which in many cases were first occupied by felt-like aegirine.

Remnants of these fracture fillings are occasionally found in the albite-analcime veins, for example those mentioned from Kangerdluarssuk and Kvanefjeld.

For these reasons it may be concluded that the albite-analcime veins were formed after the consolidation of the naujaite. The veins may be continuous with veins of lujavrite and only in exceptional cases intersect lujavrite. It has therefore been assumed that these veins have been formed from fluids squeezed out from the crystallizing lujavrite magma which is considered a residual magma enriched in volatiles and rare elements (SØRENSEN, 1962, p. 174). In accordance with this interpretation the lujavrites are generally fine-grained and strongly laminated with bent laths of feldspar; pegmatites are rare.

The tugtupite-bearing veins of Ilímaussaq are generally composed of typically pneumatolytic-hydrothermal minerals and only rarely are there zoned bodies of pegmatitic type. These pegmatites are especially associated with a medium- to coarse-grained lujavrite with "subdoleritic" texture which injects the naujaites, syenites, fine-grained lujavrites and the lavas of the roof in the Kvanefjeld area (cf. SØRENSEN et al., 1969). As mentioned on p. 28 the cores of these pegmatites are composed mainly of analcime and natrolite and closely resemble the analcime veins found elsewhere in Ilímaussaq. This association of true pegmatites with a non-laminated, fairly coarse-grained lujavrite indicates that only when the volatiles were retained in the lujavrite magma could pegmatites be formed. In the case of consolidation of lujavrite magma during deformation, the fluids were expelled and formed veins composed of the minerals which in the case of quiet crystallization would have formed the cores and replacement bodies of pegmatites.

The predominance of albite-analcime veins over late pegmatites in Ilímaussaq is in striking contrast to the scarcity of such veins and the predominance of pegmatites in Lovozero (see VLASOV et al., 1959).

The beryllium-bearing veins in Lovozero are interpreted by VLASOV et al. as complex pegmatites associated with poikilitic sodalite syenites. These pegmatites are often zoned and have replacement bodies composed of one or several of the following minerals: albite and/or microcline, analcime, natrolite and ussingite. Ussingite is considered to be late and replaces sodalite, prismatic natrolite and microcline. Chkalovite occurs near the margins of ussingite-rich bodies and is furthermore associated with natrolite, sodalite, schizolite, neptunite, sphalerite, steenstrupine and murmanite. There are practically no inclusions in the chkalovite (VLASOV et al., 1959; YAKOVLEVSKAJA & SEMENOV, 1963). The chkalovite-ussingite pegmatites are often subject to an intense hydrothermal reworking resulting in natrolitization of sodalite and ussingite, while chkalovite is replaced by epididymite, tugtupite or sphaeroberttrandite.

According to VLASOV et al. (1959) eudidymite-epididymite in Lovozero is associated with albite-rich replacement bodies and may occur in leaching cavities in albite or natrolite. The associated minerals are fluorite, albite, natrolite, neptunite and schizolite; beryllite, sphaerobertandite and gelbertrandite are products of alteration. Genthelvitite occurs in hybrid pegmatites and leucophane forms spherulites in natrolite druses.

Thus the beryllium minerals of Lovozero were formed at a late stage under hydrothermal conditions.

The beryllium-bearing veins in Ilímaussaq are composed mainly of the minerals characteristic of the beryllium-bearing replacement bodies in the pegmatites of Lovozero. One might then ask if the patches of microcline, sodalite, eudialyte and aegirine found in the beryllium veins could be remnants of otherwise completely replaced naujaite pegmatites. The fact that the veins are sometimes found in zones of deformation in naujaite, and that they are closely associated spatially with lujavrite, makes it most likely that they are related to the lujavrites rather than to the naujaites, as already suggested above. This view is supported by the local occurrence of bleached inclusions of lujavrite in some of the albite-analcime-ussingite veins.

Paragenesis

The tugtupite-bearing veins studied in Ilímaussaq display rather pronounced paragenetic relations.

Minerals such as microcline, sodalite, eudialyte-eucolite and aegirine are of early formation. One, several or all of them may be lacking in individual veins. Microcline may be associated with felt-like aegirine.

Minerals such as ussingite, chkalovite, lovozerite, epistolite and prismatic crystals of schizolite appear to be closely related in time. The ussingite replaces microcline and sodalite and may be intersected by veins of fine-grained natrolite. There may be beryllite on cracks in the chkalovite. As the veinlets of fine-grained natrolite and beryllite are cut by the albite, they were apparently formed earlier than this mineral.

Albite appears to occur in several generations. Early sugary-grained albite is succeeded by cleavelanditic albite (and flat crystals in cavities), which again in some veins appears to be embedded in a matrix of fine-grained albite rich in fluorite.

Associated with the albite are analcime, sphalerite, steenstrupine and acmite. The analcime may have been formed from volatile-enriched fluids enclosed in the albitites. Around the patches of analcime there may be concentrations of steenstrupine and sometimes also of yellow

sodalite and tugtupite. In some veins the cleavelanditic albite is intersected by veinlets of fine-grained natrolite.

The tugtupite is often associated with analcime and may penetrate not only into albite and analcime but also into the large grains of chkalovite and their crack fillings of beryllite. Li-mica, epistolite (+ gerassimovskite and nenadkevichite) and sometimes niobophyllite and monazite (or rhabdophanite) may be associated with the tugtupite. Tugtupite often forms veinlets in the albitites.

Later than the tugtupite are crusts and cavity fillings of tetragonal natrolite and chabazite (?) and the lamellar aggregates of pyrochlore, neptunite and igdloite (which may, however, be pseudomorphs after epistolite).

The fine-grained albite may also be of late formation; it is associated with fibrous aggregates of schizolite and katapleite.

It should be emphasized that all stages of the evolution mentioned above are rarely present in one and the same vein.

In the pure ussingite-chkalovite veins tugtupite is generally lacking or is present in very insignificant amounts. In a few specimens chkalovite occurs in albititic veins without any trace of tugtupite. These veins are poor in analcime. This chkalovite may have beryllite on cracks and marginal epididymite and eudidymite which again may be partially replaced by bertrandite (ANDERSEN, 1967) or gelbertrandite (?).

In the albitites containing epididymite-eudidymite (SEMENOV & SØRENSEN, 1966) there is no chkalovite. Tugtupite and Li-mica are associated with analcime, and there is late genthelvite and leucophane.

Finally it should be mentioned that in drill hole no. 22 on the Kvanefjeld plateau tugtupite and analcime appear to be late members of an association containing eudialyte, microcline, albite, nepheline, aegirine, sorensenite and other minerals.

Thus, while chkalovite is an early mineral in the veins, epididymite-eudidymite associated with albite are later and tugtupite with analcime later still. In accordance with this, tugtupite appears to be formed at least partly at the expense of chkalovite, sorensenite and perhaps epididymite-eudidymite.

The reason why there are several stages of formation of albite and natrolite and why beryllite appears to be an early product of alteration of chkalovite may be that there are several intrusive phases of lujavrite so that hot fluids have been squeezed into fractures in naujaite at intervals and from different lujavritic sources.

Preliminary examinations of fluid inclusions in some minerals from Ilímaussaq (SOBOLEV et al., 1970) have given the following temperatures of homogenization of primary liquid-gas inclusions:

sorensenite 400–420°C, tugtupite 440–460°C, chkalovite 860–980°C.

These temperatures have not been corrected for pressure of formation. The significance of the high temperature of homogenization of chkalovite will be discussed in a later paper. The temperatures of homogenization of sorensonite and tugtupite are within the range of temperatures estimated by SØRENSEN (1962).

Thus tugtupite appears to have been formed hydrothermally more or less at the same time as analcime and Li-mica. Like these two minerals it often forms crystals lining cavities in albitite, and in places it appears to have filled cavities lined by crystals of albite and microcline. It is very likely that the beryllium content of the fluids involved in the formation of these minerals is partly derived by leaching of the agpaite rocks adjacent to the fractures through which the fluids percolated, and partly a primary component of the residual magmatic fluids. The agpaite rocks of Ilmaussaq are, according to GERASIMOVSKII (1968), exceptionally rich in beryllium and lithium, with average contents of these two metals of 30 ppm and 310 ppm respectively. In Lovozero the average contents are 8.7 ppm Be and 55 ppm Li; the average values found in granites are 6.5 ppm Be and 40 ppm Li.

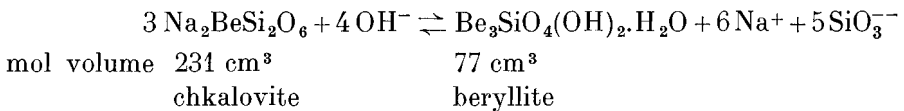
Chkalovite and sorensonite appear to have been deposited directly from the alkaline fluids; epididymite-eudidymite are partly primary, partly formed at the expense of chkalovite. Beryllite is mainly secondary, as is

Table 6. *Chemical analyses of chkalovite, tugtupite, beryllite and eudidymite from the Ilmaussaq intrusion (weight percent)*

	Chkalovite	Tugtupite (beryllium) sodalite)	Beryllite	Eudidymite
SiO ₂	57.78	51.58	31.0	72.53
BeO	12.56	5.40	38.0	10.39
Al ₂ O ₃	—	11.15	—	0.65
Fe ₂ O ₃	tr.	tr.	0.2	0.16
MgO	0.16	0.20	—	—
CaO	—	—	—	0.60
Na ₂ O	29.20	25.52	—	11.91
K ₂ O	0.09	0.12	—	0.20
H ₂ O ⁺	—	—	22.7	} 4.11
H ₂ O ⁻	0.02	0.03	6.8	
S	0.17	0.33	—	—
Cl	0.14	7.28	—	—
Total	100.12	101.61	98.7	100.55
Analyst	ME MOURITZEN	ME MOURITZEN	I. SØRENSEN	M. E. KAZAKOVA
Reference	SØRENSEN (1962)	SØRENSEN (1962)	ANDERSEN (1967)	SEMENOV & SØRENSEN (1966)

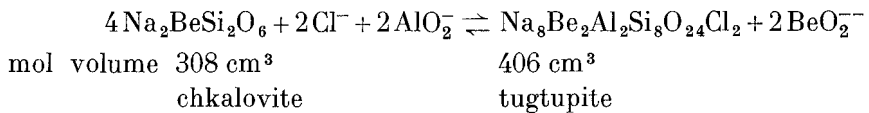
tugtupite which is formed at the expense of chkalovite or sorensenite, although in some cases (as when occurring in crystal cavities) tugtupite and beryllite also appear to be precipitated directly from the fluids involved.

As seen in table 6 the formation of beryllite at the expense of chkalovite represents a very strong leaching of SiO_2 and Na_2O so that the alteration product is strongly enriched in beryllium and water. The removal of SiO_2 and the precipitation of beryllium indicate an alkaline environment:



As demonstrated by ANDERSEN (1967) the association of beryllite and sorensenite may be interpreted as a result of a forceful injection of Be-rich solutions into a consolidated rock. This is because beryllite occurs on fractures in sorensenite which appears to be chemically unaltered. However, the beryllite in chkalovite described by ANDERSEN (1967) is clearly a product of alteration of the chkalovite. Beryllite may therefore partly have been formed as an alteration product of chkalovite, and partly as a precipitate from residual solutions in cavities when beryllium complexes are made unstable (BEUS, 1966).

A possible scheme for the transformation of chkalovite into tugtupite may be written:



This process takes place under such alkaline conditions that some beryllium is removed in the form of beryllate ions. There is no evidence of redeposition of the released beryllium.

The difference in mol volume may explain the observation that grains of chkalovite subjected to replacement by tugtupite are often shattered (chkalovite: $V_0 = 3058 \text{ \AA}^3$, $Z = 24$; tugtupite: $V_0 = 658 \text{ \AA}^3$, $Z = 1$).

An indication of the alkaline conditions prevailing during the formation of tugtupite is the association of tugtupite and analcime.

Sodium-fluorine complexes of beryllium, which are stable in near neutral solution, may also participate in the transportation of the dissolved beryllium and may have been operative in the formation of epididymite-eudidymite, which are generally associated with albite and fluorite and thus may have been formed from weakly acid solutions. In

Khibina and Lovozero the albite-epididymite-bearing veins may also contain quartz (VLASOV et al., 1959; BEUS, 1966).

In conclusion, it appears that tugtupite has been formed from alkaline aqueous fluids at temperatures around 400°C and at a fairly high volatile pressure since S and Cl take part in the crystallization of the mineral, and since the replaced anhedra of chkalovite often are shattered.

The sequence beryllite-epididymite-tugtupite may indicate that the solutions at the stages during which these minerals were formed were respectively alkaline – neutral (or acid) – strongly alkaline. This may reflect an advancing wave of hydrothermal solutions, as discussed by KORZHINSKY in a number of papers (for instance KORZHINSKY, 1959). The writers favour, however, the view that there have been several injections of hydrothermal fluids into vein systems. Residual fluids were squeezed out from successive injections of lujavrite magma at different stages of crystallization. As they have travelled different distances through the rocks, it is reasonable to assume that the various residual fluid phases have differed from one another with respect to chemical composition, temperature and vapour pressure.

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PLATES

Plate 1

- Fig. 1. No. 77450,3: Tugtupite. Kvanefjeld: Pseudocubic penetration triplet in tugtupite. The twin planes are $\{101\}$. The microphotograph has been taken with crossed nicols, $\lambda = 491$ nm and with addition of a phase difference of app. 440 nm to make the $\langle 001 \rangle$ section nearly black but the $\langle 100 \rangle$ and the $\langle 010 \rangle$ sections different. $\times 19$.
- Fig. 2. No. 21059. Tugtup agtakórfia. $23.8\times$, + nic.: Shattered grain of chkalovite. The single fragments show undulatory extinction and are separated by zones of crushing made up of aggregates of chkalovite with some tugtupite. Note lines of fluid inclusions (healed fractures) in the chkalovite.
- (H. MICHEESEN phot.).



Fig. 1

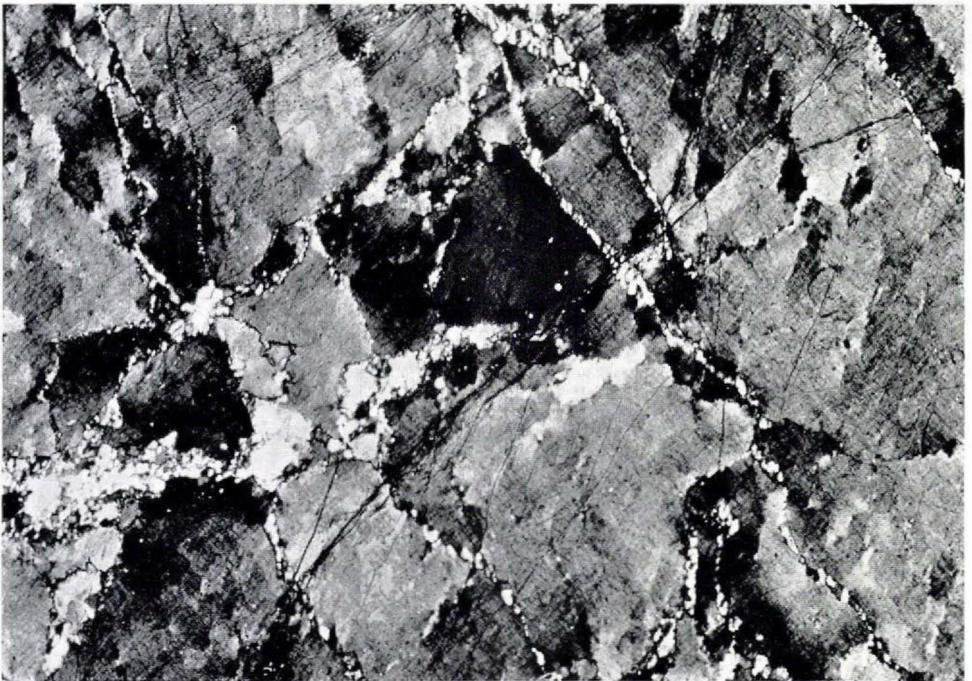


Fig. 2

Plate 2

- Fig. 1. No. 21059,2. Tugtup agtakórfia. $23.8\times$, + nic: Anhedron of chkalovite (upper half) veined by fine-grained tugtupite with inclusions of chkalovite branching out from larger and more coarse-grained aggregate of tugtupite. Note the twinning of the tugtupite.
- Fig. 2. No. 3 a. Tugtup agtakórfia. $23.8\times$, + nic: Stellar aggregates and single crystals of microcline enclosed in tugtupite. The tugtupite is enclosed in albite and contains corroded inclusions of the latter. All minerals are cut by thin veinlets of tetragonal natrolite.
- (H. MICHEELSEN phot.).

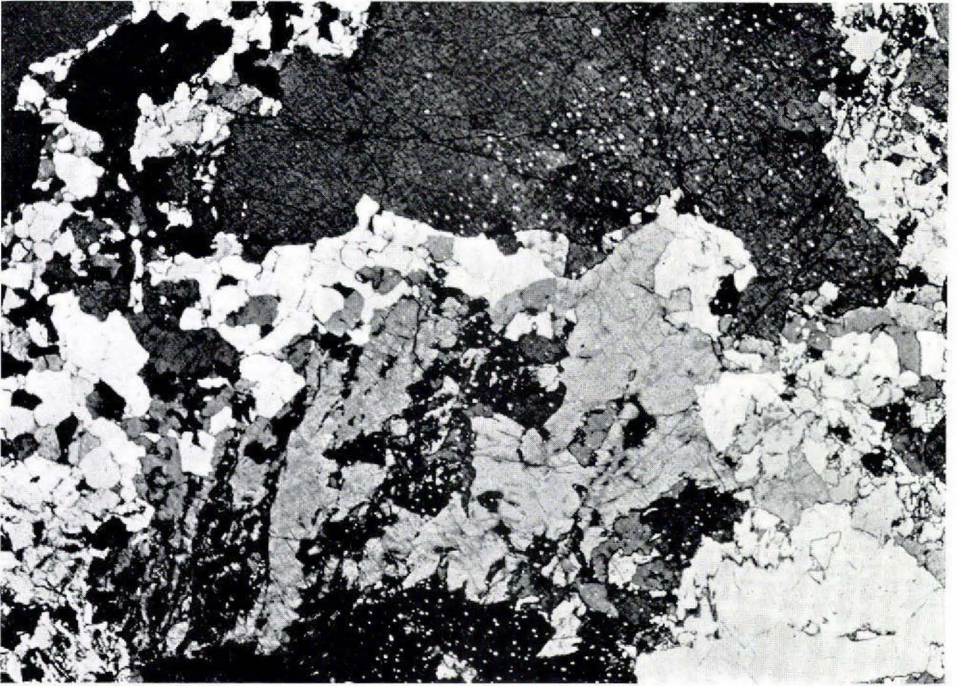


Fig. 1

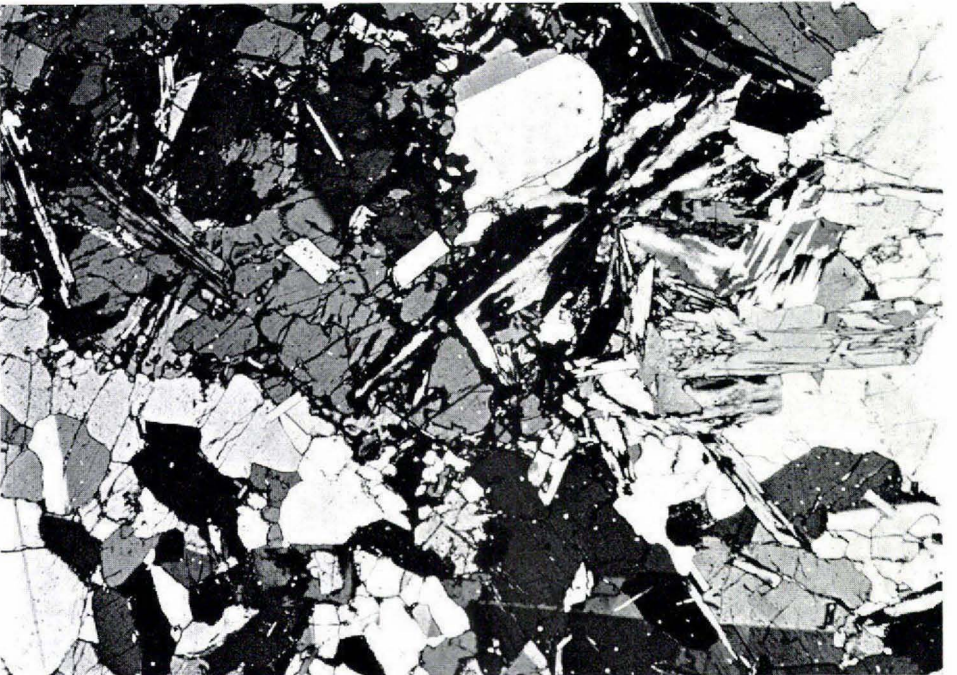


Fig. 2

Plate 3

Fig. 1. No. 77231. Head of Kangerdluarssuk. $23.8\times$, + nic: Border zone of fine-grained aegirine (top) and zone of sodalite (bottom). Between these zones there is a fine-grained aggregate of albite and microcline which also occupies cleavage fractures in the sodalite.

Fig. 2. No. 66134. Head of Kangerdluarssuk. $23.8\times$, + nic: Fine-grained albitite with amoboid-shaped areas of analcime having cores of sodalite. There are small needles of aegirine in the albitite.

(H. MICHEELSEN phot.).

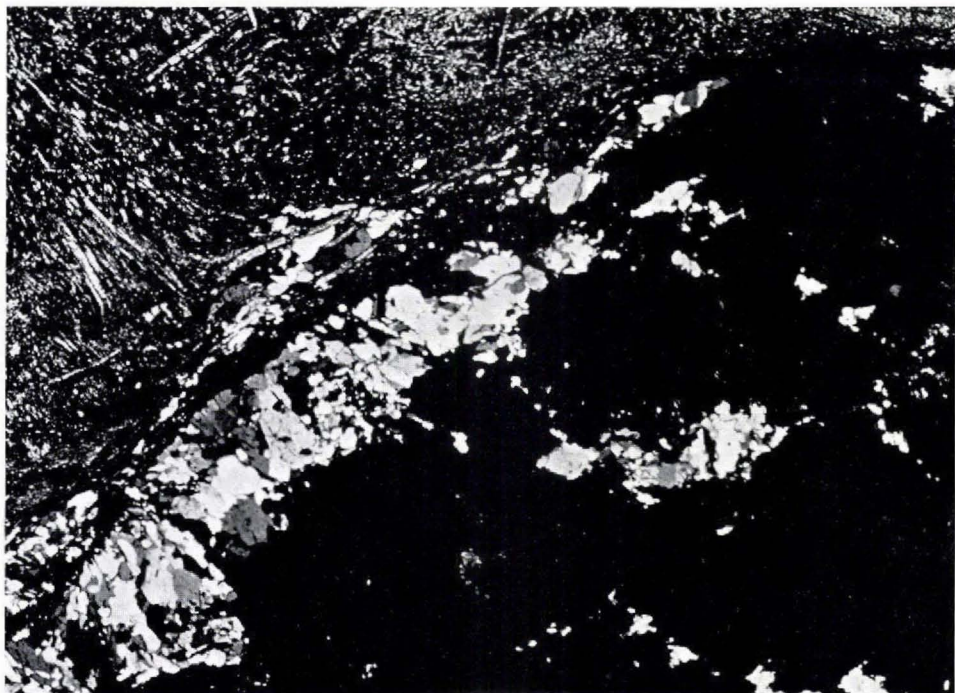


Fig. 1

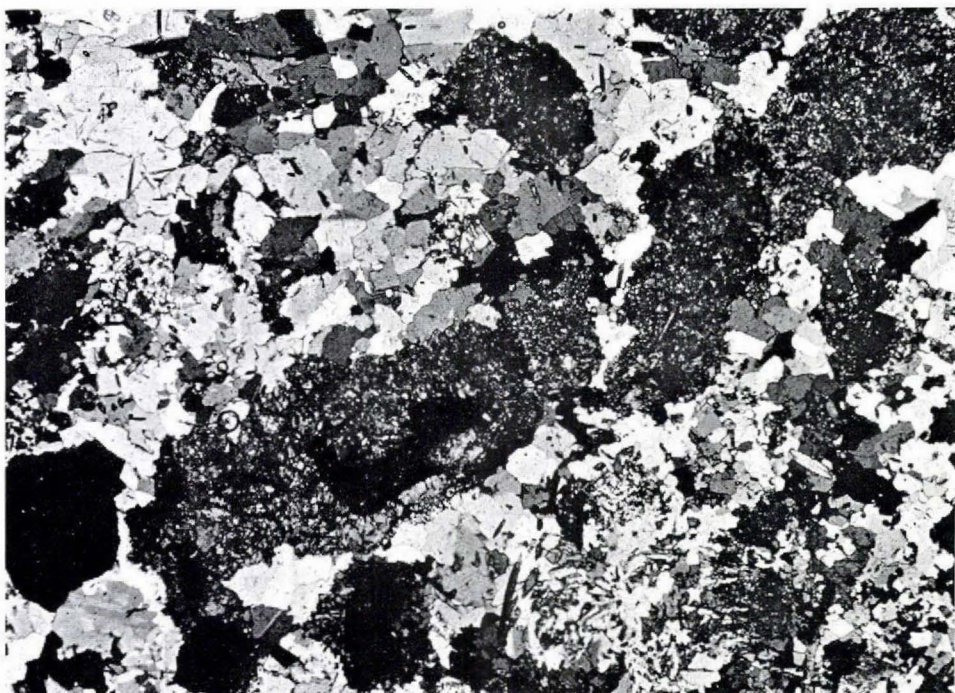


Fig. 2

Plate 4

Fig. 1. No. 66135 c. Head of Kangerdluarssuk. $23.8\times$, + nic. Interfingering of cleavelanditic albite (right) with fine-grained albitite (left). The latter has elongated areas of analcime (black).

Fig. 2. No. 66133 a. Head of Kangerdluarssuk. $23.8\times$, + nic. Border of tugtupite veinlet (bottom) having flakes of Li-mica in contact with albitite.

(H. MICHELSEN phot.).

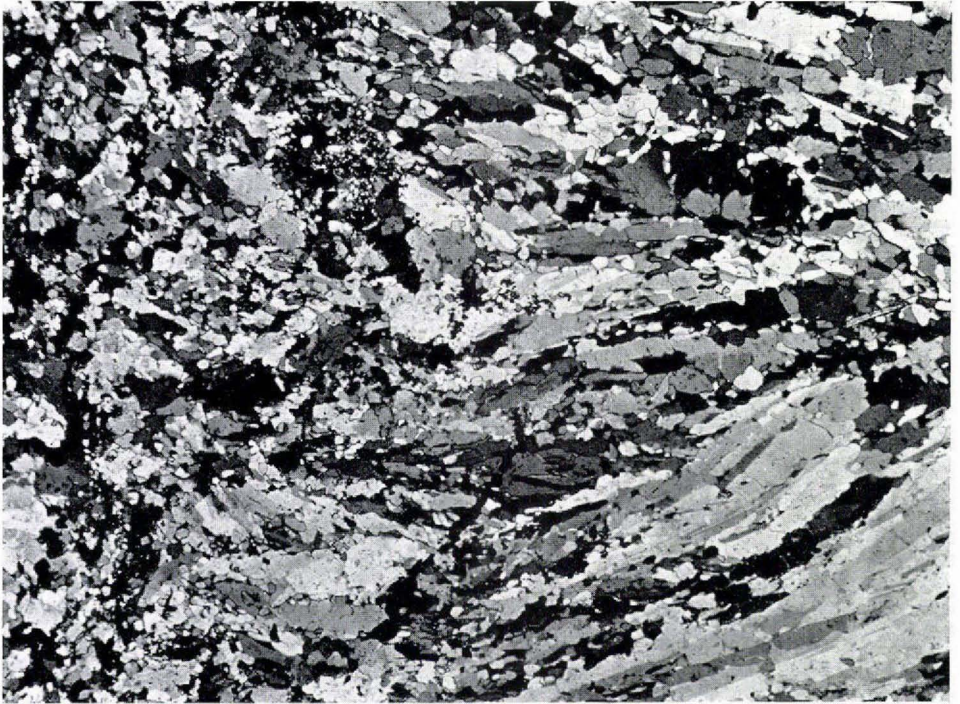


Fig. 1

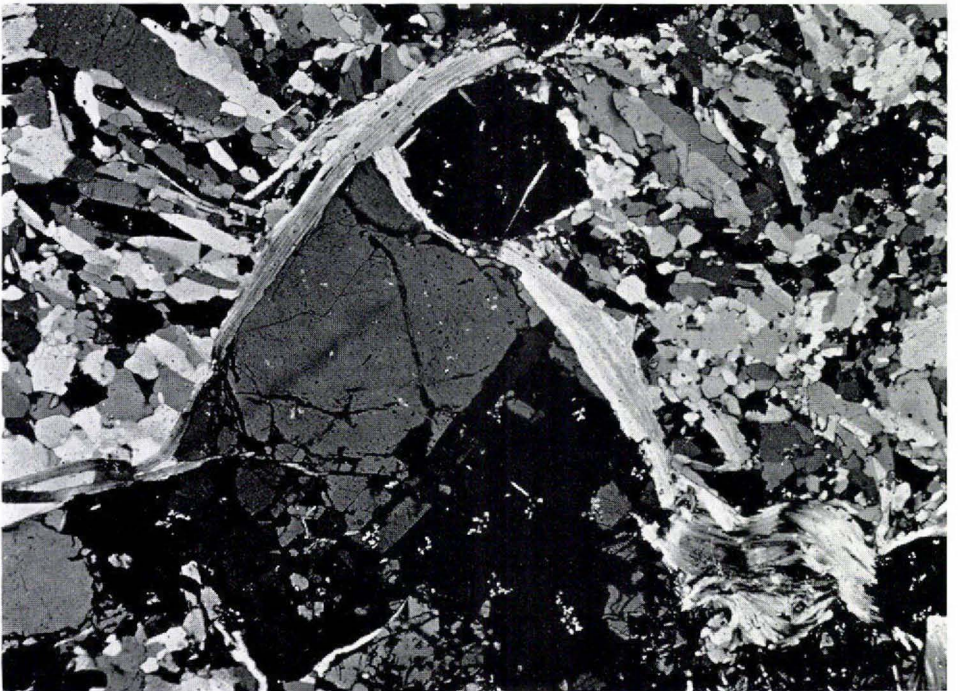


Fig. 2

Plate 5

- Fig. 1. No. B.2. Head of Kangerdluarssuk. $23.8\times$, + nic. "Foliateous" albite cut by veinlets of fine-grained natrolite.
- Fig. 2. No. 64901 b. Head of Kangerdluarssuk. $23.8\times$, + nic. Albite (bottom) with interstitial ussingite veined by fine-grained natrolite. Upper left corner: larger mass of ussingite veined by fine-grained natrolite. Upper right corner: twinned tugtupite with inclusions of albite and ussingite and with a partial rim of sodalite (black).

(H. MICHEELSEN phot.).



Fig. 1

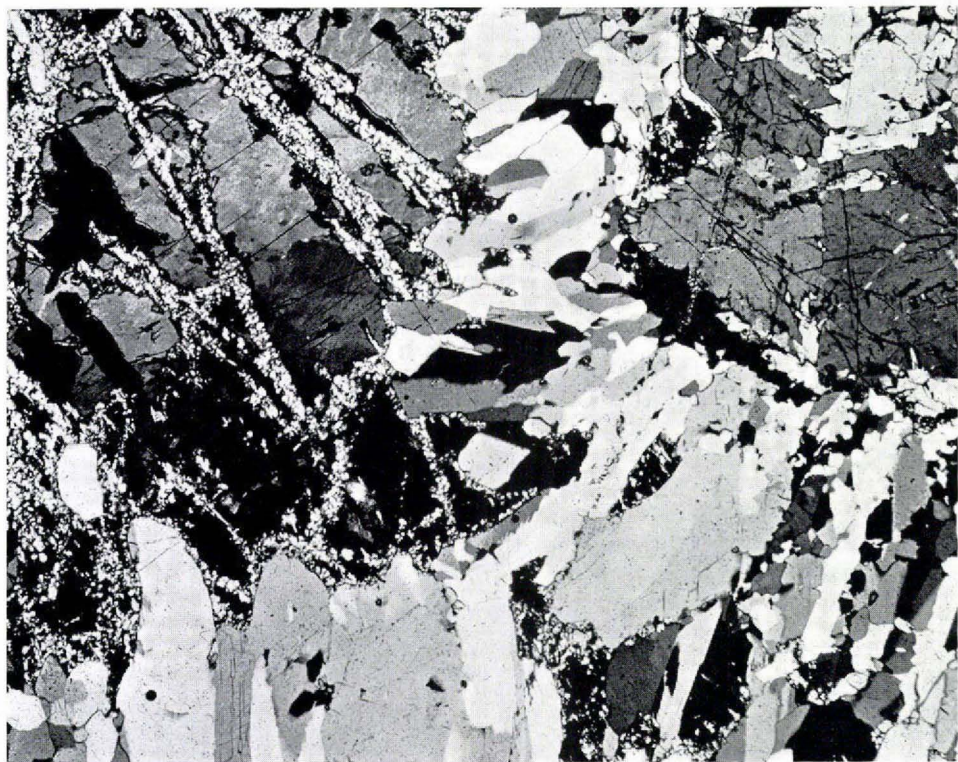


Fig. 2

Plate 6

Fig. 1. No. 77227 a. Head of Kangerdluarssuk. $23.8\times$, + nic. Patches of ussingite veined by natrolite (centre top) separated by zone of sodalite and flakes of Li-mica from tugtupite which is the most abundant mineral on the photo.

Fig. 2. No. 64750,1 Kvanefjeld. $23.8\times$, + nic. Mass of tugtupite (bottom) into which crystals of albite protrude.

(H. MICHEESEN phot.).

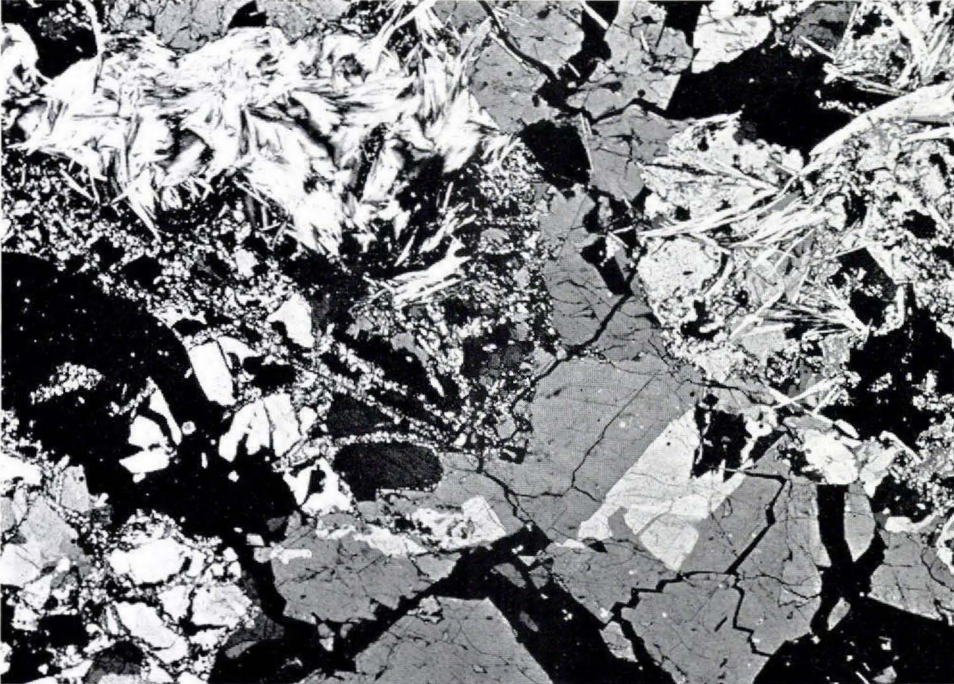


Fig. 1



Fig. 2

Plate 7

Fig. 1. No. 64750,2. Kvanefjeld. $23.8\times$, + nic. Analcime (top) and chkalovite (bottom). There is a thin zone of tugtupite between these two minerals (centre). Most of the black areas of the tugtupite rim are due to holes in the thin section.

Fig. 2. No. 77450,3. Kvanefjeld. $23.8\times$, + nic. Chkalovite penetrated by tugtupite which contains small needles of aegirine.

(H. MICHEELSEN phot.).

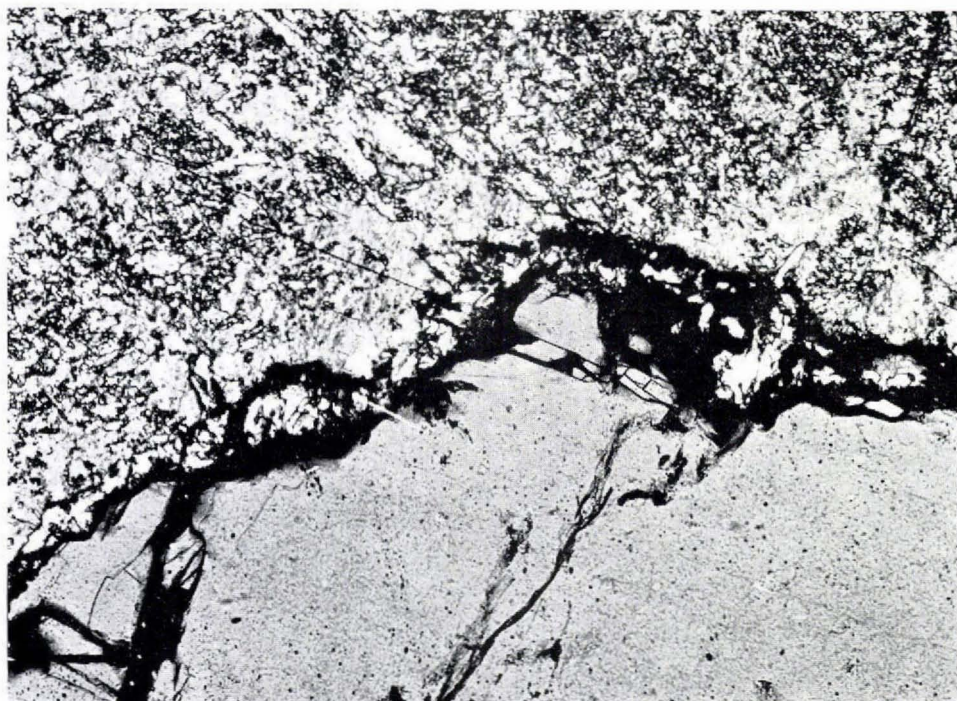


Fig. 1

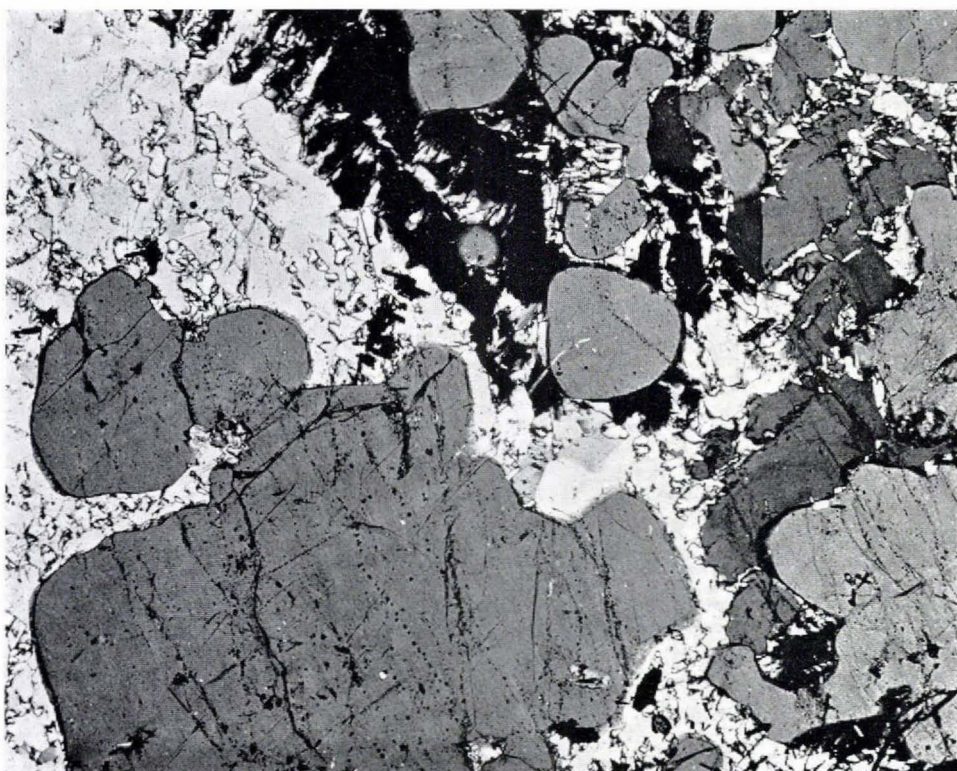


Fig. 2

Plate 8

- Fig. 1. Drill core 22-63.92. Kvanefjeld. $23.8\times$, + nic. Group of sorensenite crystals (centre) enclosed in tugtupite which displays coarse twinning (top) and fine twinning (bottom). There are partially corroded crystals of microcline in the tugtupite.
- Fig. 2. No. 77252 a. The Taseq slope. $23.8\times$, + nic. Corroded and partially crushed crystals of chkalovite cut by granulated zone of chkalovite with subordinate tugtupite. Bottom left: fine-grained matrix of ussingite with aggregates of tetragonal natrolite needles.
- (H. MICHEELSEN phot.).

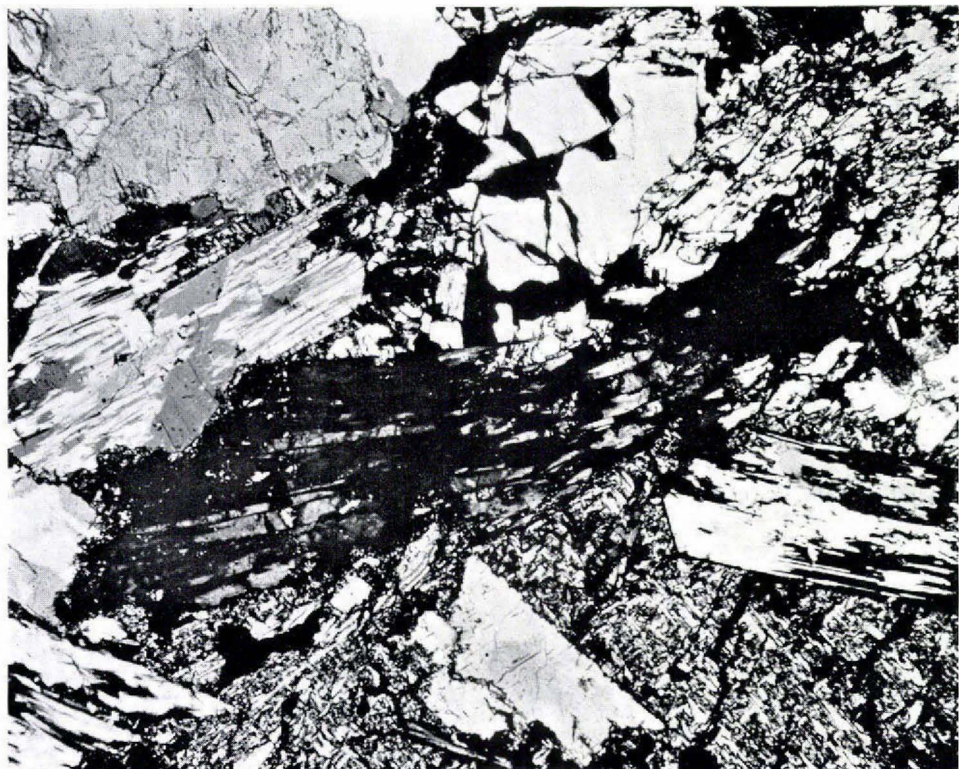


Fig. 1

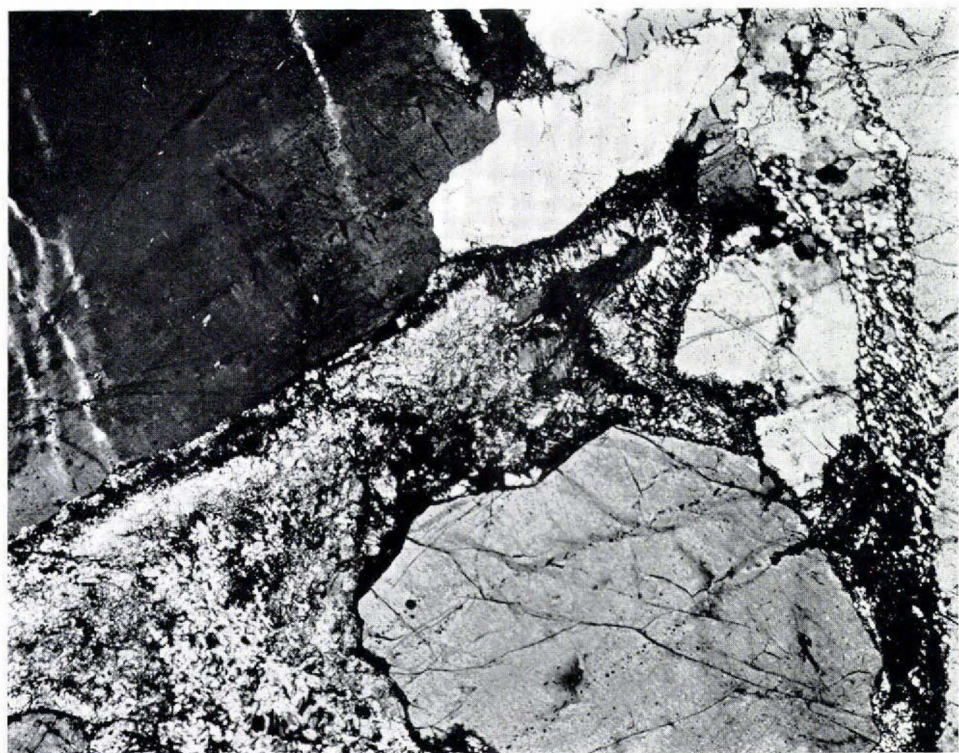


Fig. 2

Plate 9

Fig. 1. No. S.1. The Taseq slope. $23.8\times$, + nic. Tugtupite (lower half) in fine-grained albitite (upper half). Note corroded crystals of microcline, albite and Li-mica in the tugtupite.

Fig. 2. No. X.2. The Taseq slope. $23.8\times$ + nic. Chkalovite intersected by thin veinlets of beryllite (black on the photograph). Top: rim of epididymite cutting the beryllite veinlets and replacing the chkalovite.

(H. MICHEESEN phot.).

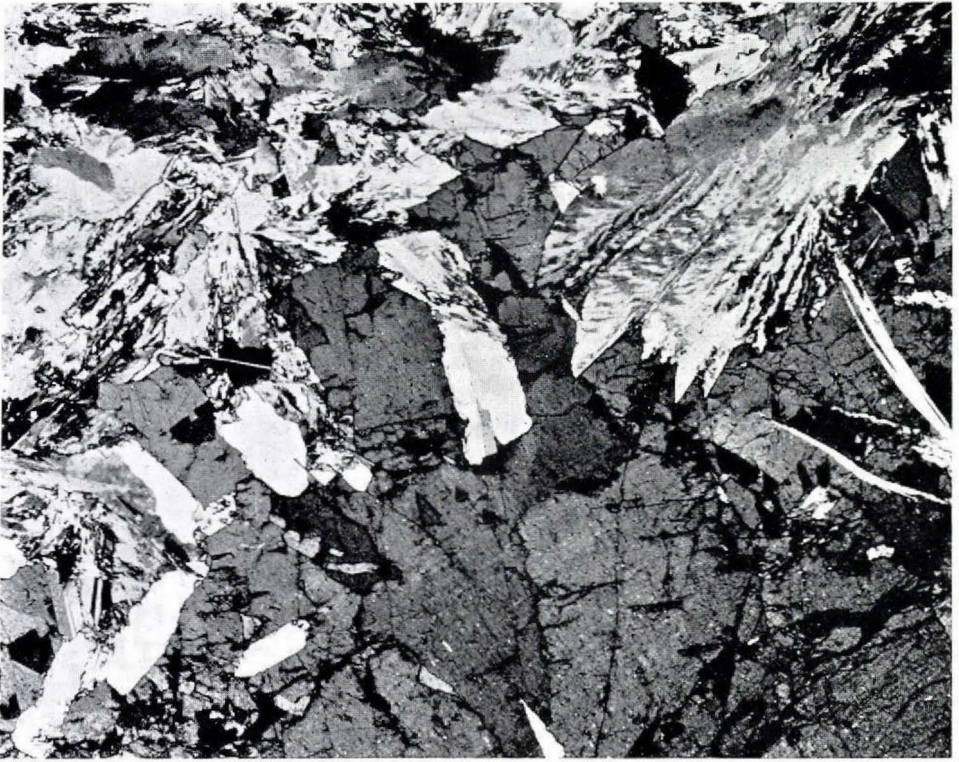


Fig. 1



Fig. 2