GRØNLANDS GEOLOGISKE UNDERSØGELSE

# A PRELIMINARY EXAMINATION OF FLUID INCLUSIONS IN NEPHELINE, SORENSENITE, TUGTUPITE AND CHKALOVITE FROM THE ILÍMAUSSAQ ALKALINE INTRUSION, SOUTH GREENLAND

CONTRIBUTION TO THE MINERALOGY OF ILÍMAUSSAQ, No. 15

BY

V. S. SOBOLEV, T. Y. BAZAROVA,
N. A. SHUGUROVA, L. SH. BAZAROV, YU. A. DOLGOV
AND H. SØRENSEN

WITH 5 FIGURES, 3 TABLES AND 4 PLATES

С РУССКИМ РЕЗЮМЕ

## Abstract

A preliminary examination has been undertaken of fluid inclusions in four minerals from the Ilimaussaq alkaline intrusion. The apparatus used in the study has been developed in the Institute of Geology and Geophysics of the Siberian Branch of the Academy of Sciences, Novosibirsk.

Primary three-phase inclusions (liquid-gas-crystals) in nepheline from naujaite homogenize in the liquid phase at 850–1040°C. The gas phase in one analysed inclusion is dominated by $CO_2$. Primary gas-liquid inclusions in nepheline from green lujavrite homogenize at 910–970°C in the liquid phase. These temperatures are in agreement with temperatures obtained on nephelines from Lovozero, Miask and Synnur and with data from fusion experiments on the rocks in question.

Primary gas-liquid inclusions in sorensenite and tugtupite from late analcime-albite veins homogenize at 400–460°C. The liquid phase of fluid inclusions in tugtupite contains 21 weight per cent of salts – sodium chloride is assumed to be predominant. The gas phase in one primary inclusion in tugtupite is dominated by $CO_2$. Secondary fluid inclusions in the two minerals homogenize at 350–100°C. The temperatures obtained are in agreement with those estimated from mineralogical evidence.

A big crystal of chkalovite from an ussingite-analcime vein contains several generations of fluid inclusions. The primary liquid-gas-crystal inclusions homogenize at 860–980°C. The solid phase is dissolved at 330–360°C, two immiscible liquids appear at 700–800°C. Half of the ca. 250 fluid inclusions examined belong to this category.

The several generations of secondary inclusions which embrace liquid-gas-crystal inclusions, gas-liquid inclusions and gas inclusions homogenize in several groups between 760°C and 100°C.

The liquid phase of the high temperature inclusions contains 40–44 weight per cent NaCl. The pressure at the temperature of homogenization is estimated to be higher than 1000 atm. The gas phase is dominated by $CO_2$ and $N_2$+ inert gases.

The unexpectedly high temperature of homogenization of the primary inclusions of the chkalovite is difficult to explain. A detailed study of this problem is in preparation.

## АННОТАЦИЯ

Предварительно исследовались жидкие включения 4 минералов из щелочного интрузива Илимауссаг. Аппаратура, используемая для этой цели, была разработана в Институте геологии и геофизики СО АН СССР, в г. Новосибирске.

Первичные включения (жидкость — газ — кристаллы-узники) в нефелине из науяита гомогенизируются в жидкую фазу при 850—1040°C. В составе газовой фазы одного анализированного включения преобладает $CO_2$. Первичные газово-жидкие включения в нефелине из зеленого луяврита гомогенизи-

руются при 910—970°C в жидкую фазу. Эти температуры находятся в согласии с температурами, полученными для нефелинов из Ловозера, Урала и Сынныра, а также с экспериментальными данными по плавлению для подобных горных пород.

Первичные газово-жидкие включения в соренсените и тугтупите из поздних анальцимо-альбитовых жил гомогенизируются при 400—460°C. Жидкая фаза включений в тугтупите содержит 21 вес. % солей с вероятным преобладанием хлористого натрия. В газовой фазе одного первичного включения в тугтупите преобладает $CO_2$. Вторичные газово-жидкие включения в обоих минералах гомогенизируются при 350—100°C. Температуры, полученные в экспериментах, находятся в согласии с температурными определениями для минералогических данных.

Крупный кристалл чкаловита из уссингит-анальцимовой жилы содержит несколько генераций газово-жидких включений. Первичные трехфазовые включения гомогенизируются при 860—980°C. Твердая фаза растворяется при температуре 330—360°C, при 700—800°C появляются две несмешивающиеся жидкости. Половина из 250 исследованных включений принадлежит этой категории.

Вторичные включения трехфазовые, газово-жидкие, а также существенно газовые представляют собой несколько генераций (групп), которые гомогенизируются в интервале температур от 760 до 100°C.

Жидкая фаза высокотемпературных включений содержит 40—44 вес. % NaCl. Давление при температуре гомогенизации, как определено, выше 1000 атм. В газовой фазе преобладает $CO_2$ (присутствует $N_2$ + инертный газ).

Чрезвычайно высокая температура гомогенизации первичных включений чкаловита трудно объяснима. Подробное изучение проблемы продолжается.

# CONTENTS

# PREFACE

This paper presents the results of a study of fluid inclusions in some minerals from the Ilímaussaq alkaline intrusion, South Greenland.

One of the authors (V. S. S.) when visiting the Institute of Petrology, Copenhagen in the spring of 1967 mentioned the progress made in the high-temperature inclusion studies in the laboratories at Novosibirsk. It was then decided to carry out a few preliminary examinations of minerals from Ilímaussaq and in case the studies were successful to take up a closer co-operation using the apparatus developed in Novosibirsk. The preliminary studies gave so interesting results that it is felt justified to publish them separately. A more detailed examination of the fluid inclusions in the minerals of Ilímaussaq is being planned.

The experimental part of the examination has been carried out in Novosibirsk, the petrological part in Copenhagen. The paper has been written jointly by all those involved in the study.

The Russian parts of the manuscript have been translated into English by Mrs. A. DEMIN. T. C. R. PULVERTAFT kindly corrected the English of the manuscript.

The publication is authorized by the Director of the Geological Survey of Greenland.

Institute of Geology and Geophysics of
the Siberian Branch of the Academy of Sciences,
Novosibirsk, May 1968

Institute of Petrology,
Copenhagen, May 1968

# INTRODUCTION

Fluid inclusions in minerals have been studied intensively for more than a hundred years. Misinterpretation of the results obtained from these studies, first of all the failure to distinguish primary and secondary inclusions, has brought this field of research into discredit, but recent work in a number of laboratories has demonstrated the value of inclusion studies to mineralogy, petrology and ore geology. The studies reported in the present paper have been carried out in the Institute of Geology and Geophysics of the Siberian Branch of the Academy of Sciences, Novosibirsk. It is based partly on the fundamental studies of ERMAKOV (1950) and LEMMLEIN (1956).

Methods have now been developed which make it possible to evaluate the physical-chemical conditions of crystallization of minerals containing fluid inclusions. The determination of the main parameters of crystallization (temperature, pressure, amount and composition of dissolved salts and gases) in primary fluid inclusions gives an idea of the conditions at the time of formation of a mineral, while the study of secondary inclusions sheds light on the post-crystallization history of a mineral. It is thus possible to characterize quantitatively the crystallization of the rocks examined and to elucidate their genesis.

The Ilímaussaq alkaline intrusion in South Greenland is made up mainly of agpaitic nepheline syenites which appear to have been formed from a per-alkaline magma strongly enriched in volatile compounds (cf. SØRENSEN, 1958).

# GENERAL PRINCIPLES

Fluid inclusions are relics of mineral-forming solutions captured either during crystallization of the minerals (the primary and pseudo-secondary inclusions) or during the post-crystallization history of a mineral, *i.e.* during healing of fractures or recrystallization (secondary inclusions). Effusive and hypabyssal rocks may contain inclusions of the melt (either in the form of glass or as partly or fully crystalline material) captured during the crystallization of phenocrysts.

Depending on the state of aggregation of the mineral-forming medium the inclusions at the moment of capture may be in a fused, liquid or gaseous state. At the moment of their capture the inclusions consist generally of a homogeneous medium exposed to a certain pressure corresponding to the pressure prevailing during crystallization of the minerals. When subjected to decreasing temperature (and pressure) the content of the cavities may split up into several phases and at room temperature may consist of two, three or more phases depending on the composition and concentration of the parental solution.

Thus, each microscopic remnant of the mineral-forming medium, when returned to a homogeneous state, carries within itself information about the thermodynamic conditions during crystallization of the mineral examined.

The study of primary inclusions reveals the temperature interval of primary crystallization of the mineral in question; the study of the secondary inclusions gives information about the low temperature boundary of crystallization.

Up to the beginning of the last decade inclusions in minerals from pegmatites and hydrothermal veins were especially studied. During the last few years inclusions in minerals formed during the magmatic stages of crystallization have been studied intensively in the Soviet Union (BAZAROVA and KOSTYUK, 1963; BAZAROVA, 1965; KOSTYUK and BAZAROVA, 1966; SOBOLEV and others, 1967).

# METHODS

**1. Temperature:** the determination of the temperature conditions during crystallization of a mineral and during its post-crystallization history may be carried out by homogenization of the inclusions of the mineral-forming solutions.

In the present study the determination of the temperatures of homogenization of the gas-liquid inclusions has been performed in the microthermochamber described by DOLGOV and BAZAROV (1965). The thermochamber works within a range of temperatures from 20°C (room temperature) to 1200°C. The temperatures are determined quite accurately within a broad range of temperatures (from room temperature up to 1600°C) by means of the platinum-platino-rhodium thermocouple.

The accuracy of the measurements is regularly controlled by the periodical adjustment of the thermochamber using the temperature of fusion of the pure chemical substances KCl, NaCl, Ag and Au. The adjustment of the thermocouple is carried out inside the chamber, which provides the accuracy necessary for this method.

Inclusions of melt are examined in a chamber of slightly different construction which works within a temperature range from room temperature up to 1600°C.

The temperatures of homogenization have not been corrected for pressure.

**2. Pressure:** the pressure in the inclusions was determined by a method worked out by BAKUMENKO and others (1965), after consideration of the recommendations of LEMMLEIN and KLEVTSOV (1956) who applied freezing in order to determine the concentration of the chlorides in inclusions. The methods used in the present examination consist in the determination of the true amount of $CO_2$ and other gases, as well as the concentrations of the dissolved salts within an individual inclusion. The total pressure in an inclusion at the temperature of homogenization (in the homogeneous state) is subsequently determined by means of diagrams.

**3. Concentration of salts in the liquid phase:** the concentration of the dissolved salts in the gas-liquid inclusions was determined by

using a device for deep freezing, working within the interval from room temperature down to $-180°$C (Bazarov, 1966). The composition of the predominant salt was determined according to a method suggested recently by Bazarov and Motorina (1967), which consists in observation of the phase transformation of a "captive" crystal subjected to cooling below $0°$C. At temperatures below $0°$C NaCl is transformed into hydrohalite—$NaCl \cdot 2H_2O$—which does not crystallize in the cubic system. Crystals of KCl, however, do not transform under cooling. This method gives a sufficient accuracy for calculation of the NaCl and KCl concentrations in multi-phase inclusions.

**4. Composition of the gas phase**: the composition of the gas phase in the inclusions was determined using a method of gas analysis of individual inclusions which has been worked out and presented in detail by Dolgov and Shugurova (1966). This method is based on the selective adsorption of the gases $H_2S$, $SO_2$, HCl, HF, $NH_3$, $CO_2$, NO, $H_2$, $O_2$, CO and the unsaturated and saturated hydrocarbons. The method makes it possible to perform gas analysis even on inclusions having diameters of less than a hundredth of a millimetre.

The sensitivity of this method is 0.5–1.0 volume per cent. The arithmetic mean deviation is 4.0 volume per cent and the mean square root deviation 0.4 volume per cent.
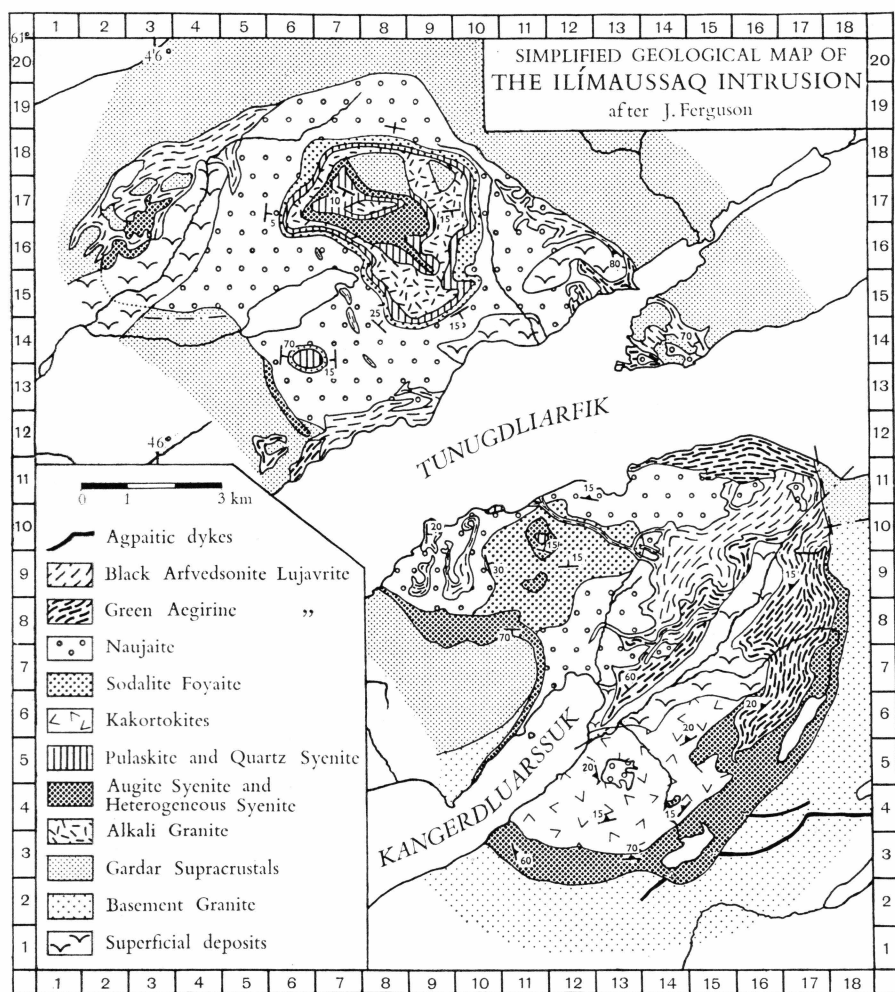
Fig. 1. Simplified geological map of the Ilímaussaq alkaline intrusion after JOHN FERGUSON 1964. The samples of naujaite, sorensenite and tugtupite were collected at the coordinate 2–3, 17; the chkalovite at 5, 15 and the aegirine lujavrite at 13, 11.

# MINERAL-THERMOMETRIC ANALYSIS
## OF NEPHELINE

Five specimens of nepheline-bearing rocks were examined during the present study of minerals from Ilímaussaq, but only two could be used. In the others there were either no fluid inclusions, or the ones present had lost their fluids because of pronounced cracking of the nepheline grains. In a sample of black lujavrite the fluid inclusions had diameters less than 0.001 mm and as the phase boundaries could

not be distinguished these inclusions could not be used in homogeniza-
tion studies. Only one sample of naujaite and one of green lujavrite
could be used.

**1. Naujaite.** The naujaite of Ilímaussaq is confined to the upper-
most part of the intrusion where it forms a horizon up to a few hundred
metres thick. It is underlain by lujavrite and is generally overlain by
sodalite foyaite although in places in the northern part of the intrusion
it is in direct contact with the volcanic rocks of the roof, into which it
sends apophyses.

The naujaite, which was first described by USSING (1912), is a
coarse-grained rock characterized by a peculiar poikilitic texture. Small
crystals of grey to green sodalite are enclosed in anhedra, several cm
across, of microcline perthite, eudialyte, aegirine, arfvedsonite and some-
times aenigmatite. Nepheline forms euhedral to subhedral grey grains
which do not display the poikilitic habit of the other essential minerals.
The nepheline grains are a few mm to a few cm across and are rich in
microlites of aegirine and/or arfvedsonite. There are often irregular
intergrowths with sodalite (USSING, 1898) and coronas of fine-grained
natrolite.

The sample studied is a drill core of villiaumite-bearing naujaite
from Kvanefjeld in the north-westernmost part of the intrusion. The
naujaite in this locality forms both small and large xenoliths in lujavrite.
The occurrence of villiaumite has been described by BONDAM and FER-
GUSON (1964).

The nepheline grains of this sample contain fluid inclusions of two
genetic types which differ from each other morphologically and with
regard to phase composition.

The primary gas-liquid multiphase inclusions are found singly or,
at most, three together in one nepheline grain when seen in thin section.
The inclusions usually form negative crystals or, rarely, are of irregular
shape. Their size reaches 0.01 mm across. The volume ratio gas:liquid:
solid is approximately 15:15:70. The vacuoles of the inclusions are
choked with solid phases which often deform the gas bubbles (see plate 1,
fig. 1). In places the gas phase is squeezed between the wall of the
vacuole and the aggregates of solid phases so that its shape at room
temperature becomes vermicular with swells and pinches. Only when
heated at temperatures around 250–300°C (when some of the solid phases
are dissolved) does the gas phase acquire the spherical shape charac-
teristic for gas inclusions in liquid.

The homogenization of the primary inclusions took place in the
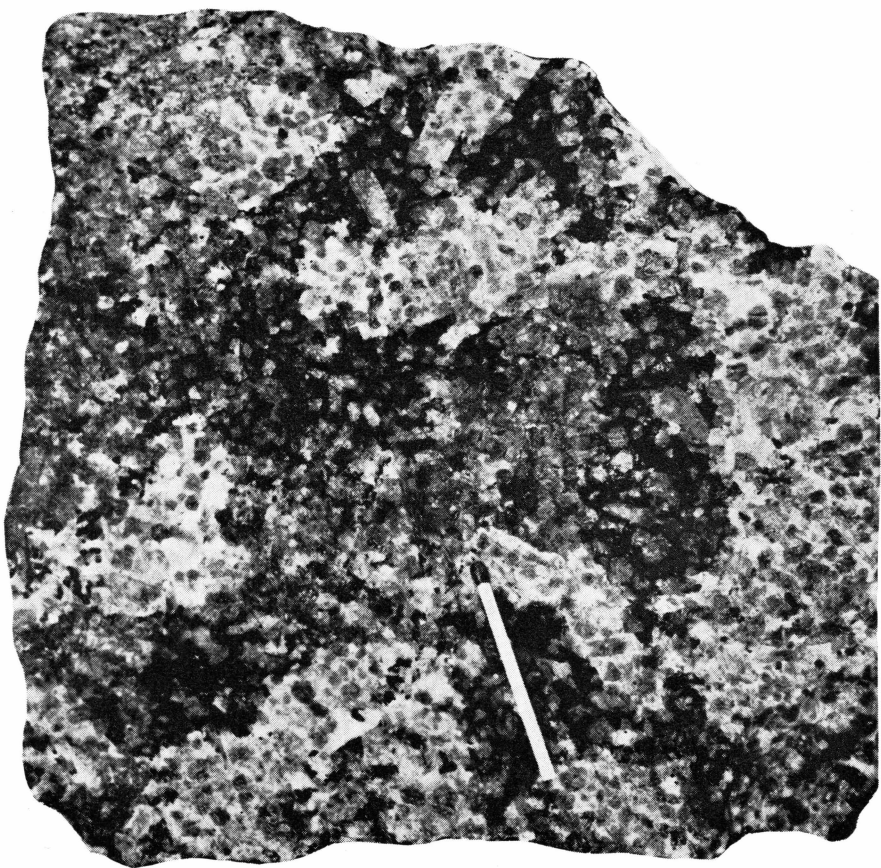liquid state at 850–1040 C.

Fig. 2. Naujaite showing crystals of sodalite (grey) which are poikilitically enclosed in microcline (white), aegirine and arfvedsonite (black) and eudialyte (dark grey). Match 4.5 cm long (*B. L. Nielsen phot.*).

Table 1. *Chemical analysis of the gas phase of a primary liquid-gas inclusion in nepheline from naujaite (in volume per cent).*
(*Analyst:* N. A. SHUGUROVA)

| Increase in volume of the gas phase during opening of the vacuole | $H_2S$, $SO_2$, $NH_3$, HCl, HF | $CO_2$ | CO | $O_2$ | $H_2$ | Heavy hydrocarbons | $N_2$ + inert gases |
|---|---|---|---|---|---|---|---|
| 18.3 times | 0.0 | 62.6 | 4.57 | 0.0 | 4.92 | 0.0 | 27.81 |

It is important to note that the chemical analysis gives only the composition of the gas phase of the inclusion (in volume per cent), and not the gas concentration in the homogeneous solution filling the vacuole at the temperature of homogenization. This could only be determined in the case when the volume of the vacuole is known.
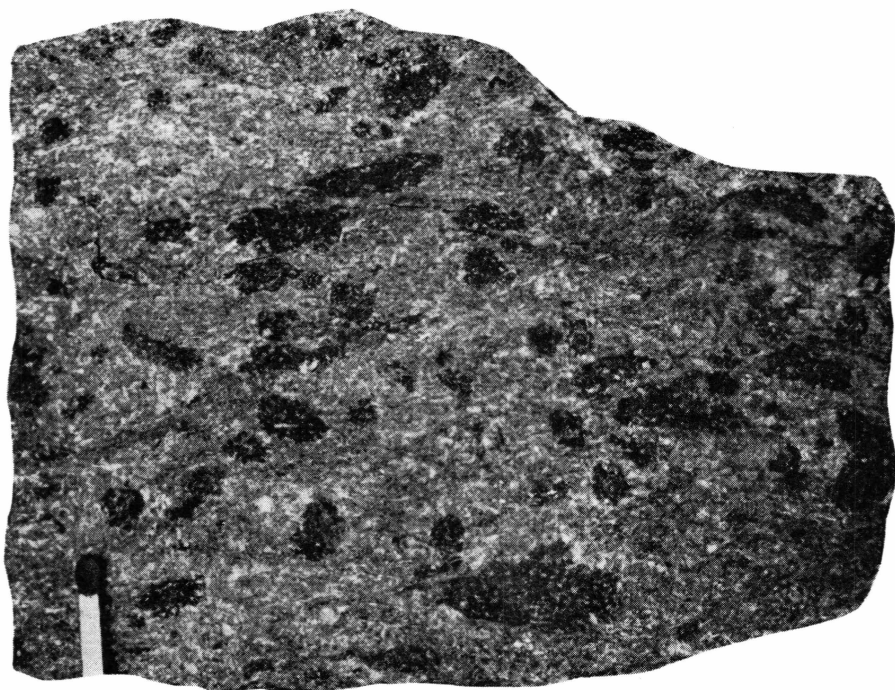
Fig. 3. Aegirine lujavrite displaying poikilitic anhedra of arfvedsonite and a laminated matrix of feldspar, aegirine and nepheline (equidimensional grey areas). Black point of match is 0.5 cm long (*B. L. Nielsen phot.*).

The dissolution of the solid phases begins at approximately 200°C and ends at about 800°C. The composition of the dissolved ions in the primary inclusions has not been determined.

A chemical analysis of one primary inclusion was performed by N. A. Shugurova. The composition of the gas phase of this inclusion is presented in table 1.

The secondary inclusions in this nepheline are represented by a dense network of bead-like chains of inclusions confined to healed fractures (plate 1, fig. 2).

**2. Green lujavrite** (no. 64840, Tuperssuatsiait). The green lujavrites occur, according to Ferguson (1964), at an intermediate level in the intrusion in a horizon of lujavrites underlying the naujaites. The major part of this horizon is made up of black, arfvedsonite-bearing lujavrites. The green, aegirine-rich lujavrites form bands or lenses in the black rock (Sørensen, 1958; Ferguson, 1964) and form thicker masses in the lowermost part of the lujavrite horizon (Ferguson, 1964).

The green lujavrite is generally a fine-grained strongly laminated rock because of the orientation of lath-like crystals of microcline and

albite, and needle-like crystals of aegirine in the planes of lamination. Small plates of eudialyte and stout prisms of nepheline, the latter being up to 0.5 cm in diameter, may also display a preferred orientation. There is often an interstitial matrix of analcime and/or natrolite. The green lujavrites frequently appear to be sheared, the texture being protoclastic.

The sample examined is a very homogeneous, finely laminated green rock with small spots, about one mm in diameter, of arfvedsonite. In thin section it is seen to be composed of laths of albite and subordinate microcline, fine needles of aegirine, small platy crystals of eudialyte and somewhat corroded short prisms of nepheline enclosed by coronas of natrolite. The parallel arrangement of feldspar laths, aegirine needles and eudialyte plates is disturbed around the nepheline grains, so that they more or less wrap the nepheline crystals. This may be due to compaction during the consolidation of the rock. There are spots of secondary natrolite and analcime and poikilitic anhedra of arfvedsonite.

The nepheline encloses small laths of microcline and small needles of aegirine and contains gas-liquid inclusions of a size less than 0.001 mm across but with comparatively distinct phase boundaries which enabled us to make about 30 reliable homogenization experiments.

The inclusions observed can be divided into two genetic groups: primary gas-liquid inclusions and secondary gas-liquid inclusions.

**The primary inclusions** are arranged parallel to the hexagonal axis of the nepheline. When seen in thin section they occur in groups of 3 to 5. The inclusions appear to be shaped as negative crystals. The ratio of gas to liquid is about 55:45. Homogenization of the inclusions was achieved by expansion of the liquid in the temperature interval 910 to 970°C.

**The secondary inclusions** are usually confined to healed fissures. Their homogenization is realised in the liquid state at temperatures below 600°C.

**3. Discussion of the results of the homogenization experiments on liquid inclusions in nepheline from naujaite and lujavrite.** According to the results of this study it may be suggested that the crystallization of the nepheline took place at temperatures not lower than 850–1040°C. The data on which this assumption is based is clearly very scanty and fragmentary. There is, however, excellent agreement with data obtained on nepheline from alkaline rocks in Lovozero (Kola Peninsula), Miask (the Urals) and Synnur, North Baikalia. For example: in the nepheline from the Lovozero urtites the temperature of homogenization of the most high-temperature inclusions varies from 850° to 980°C (BAZAROVA, 1965) and slightly higher, in nepheline from the

Uralian miaskites from 800° to 950°C, in nephelines from the North-Baikalian synnyrites from 810° to 950°C and slightly higher (PANINA, 1966). In a number of cases these inclusions are also rich in dissolved salts; this especially concerns inclusions in nephelines from the urtites of Lovozero and the miaskites of the Urals. The high temperature inclusions in these Soviet examples have, however, generally lower concentrations of dissolved salts than the nepheline of the naujaite.

The data obtained is also in fair agreement with the results of experimental studies of naujaite and lujavrite from Ilímaussaq obtained by PIOTROWSKI and EDGAR (1969). The crystallization of fused samples of naujaite were studied at atmospheric pressure and at 1030 bars water pressure. At atmospheric pressure the order of separation (and corresponding liquidus temperatures) were for naujaite (no. 57041): sodalite (1187°C), nepheline (1120°C), eudialyte (1095°C), feldspar (1080°C), clinopyroxene (1022°C), amphibole (932°C); and for green lujavrite (no. 57033): feldspar (1102°C), clinopyroxene (1095°C), nepheline (1062° C), eudialyte (? 1062°C), amphibole (1042°C). At 1030 bars $P_{H_2O}$ for naujaite: sodalite (895°C), nepheline (? 865°C), eudialyte (845°C), feldspar (800°C), clinopyroxene (745°C), amphibole (685°C); and for the green lujavrite: feldspar (875°C), clinopyroxene (845°C), nepheline (? 775°C), amphibole and eudialyte (750°C).

It is a remarkable fact that liquid inclusions homogenize at such high temperatures as about 900°C without showing critical phenomena.

It should finally be pointed out that the gas phase is made up mainly of $CO_2$ in the only primary inclusion analysed chemically.

# MINERAL-THERMOMETRIC EXAMINATION OF SORENSENITE, TUGTUPITE AND CHKALOVITE

Sorensenite, tugtupite and chkalovite all occur in late veins intersecting the agpaitic nepheline syenites of Ilímaussaq. These veins are interpreted as pneumatolytic-hydrothermal formations genetically associated with the lujavrites. The veins clearly were formed later than the consolidation of the naujaite since they are often located in zones of crushing or faulting in the naujaite. The veins do not generally intersect the lujavrites but there are veins and lenses in a special type of coarse-grained lujavrite in the Kvanefjeld area (SØRENSEN and others, 1969).

The veins often have marginal aegirine (or acmite) and are made up of one or more of the minerals: albite, sodalite, analcime, natrolite, ussingite and microcline. There are locally high concentrations of rare minerals containing rare earth metals, thorium, lithium, niobium, beryllium, zinc, *etc.*, for example steenstrupine, monazite, lithium mica, epistolite, pyrochlore, chkalovite, tugtupite, sphalerite (see SØRENSEN, 1962 and 1967).

In the present paper are recorded the results of the first mineralo-thermometric examination of sorensenite, tugtupite and chkalovite from the Ilímaussaq intrusion. The results obtained give only an approximate idea about the conditions of formation of these minerals, since the quantities of sorensenite and tugtupite available were not sufficient for a full experimental study. Furthermore sorensenite is only slightly transparent in slides. The pronounced cleavage of sorensenite is a substantial obstacle for carrying out experiments on the homogenization of fluid inclusions. Only chkalovite has been the subject of a full mineralo-thermometric analysis. Unfortunately, however, only one sample of this mineral has been examined so far.

**1. Sorensenite.** Sorensenite was first described by SEMENOV and others (1965). It occurs in analcime veins and lenses associated with a coarse-grained type of lujavrite found so far mainly in the Kvanefjeld area (SØRENSEN and others, 1969). In addition to analcime the veins are made up of natrolite and sodalite with minor pyrochlore, neptunite, blue apatite, monazite, chkalovite, beryllite, etc. Sorensenite may be the next most abundant mineral of the veins but generally occurs as

scattered lath-like or prismatic crystals up to 10 cm long. The prismatic crystals often form clusters. The sorensenite may be associated with large grains of chkalovite and may be covered by secondary beryllite (Semenov and others, 1965; Andersen, 1967). Sorensenite has also been found in association with tugtupite which appears to replace the sorensenite (Sørensen and others, in preparation).

The sorensenite examined by us contains numerous gas-liquid inclusions. Owing to the low transparency of the mineral in the thin sections studied the phase boundaries are indistinct in most of the inclusions. Because of the pronounced cleavage of sorensenite 95 % of the inclusions suitable for examination leak during the first stages of heating.

During the examination of sorensenite two types of gas-liquid inclusions were observed: a. primary and b. secondary.

Table 2. *Temperatures of homogenization of fluid inclusions in sorensenite, tugtupite and chkalovite.*

| Mineral | Genetic type of inclusions | Types of inclusions | Size of inclusions in mm | Aggregate state | Temperature of homogenization in C°*) | Remarks |
|---|---|---|---|---|---|---|
| Sorensenite | Primary? | Two-phase | Thousandths of a mm | Liquid | 420–400 | |
| | Secondary | — — | | — | 300–150 | |
| Tugtupite | Primary | Two-phase | Up to 0.001 mm | Liquid | 460–440 | |
| | Secondary | — — | — — | — | 350–310 | |
| | — | — — | — — | — | 260–240 | |
| | — | — — | Up to 0.02 mm | — | 110–100 | |
| Chkalovite | Primary? | Three-phase | Up to 0.01– 0.03 mm | Liquid | 980–860 | |
| | Secondary | — — | — — | — | 760–720 | |
| | — | Two-phase | — — | — | 600–550 | |
| | — | Four-phase | — — | — | 530–500 | |
| | — | Three-phase | — — | — | 420–400 | |
| | — | — — | — — | — | 160–140 | |
| | — | Substantially gas | — — | Gas | Lower than room temperat. | Condensation of the liquid phase when cooled below 0° C. |

*) Here and in the text the temperatures of homogenization are given without corrections for pressure.

**a. The primary gas-liquid inclusions** are arranged parallel to the elongation of the mineral. The shape of the inclusions is usually faceted (negative crystals, plate 1, fig. 3). The phase ratio gas:liquid is about 30:70. The size of the inclusions does not exceed a few thousandths of a millimetre. The temperature of homogenization of the inclusions varies from 420° to 400°C; the process takes place in the liquid state. At approximately this temperature the mineral becomes irreversibly dull and completely unsuited for further examination. Owing to this fact it has been impossible to analyse the gas phase of the inclusions.

**b. The secondary inclusions** are confined to healed fractures in the host mineral. The shape of the inclusions is usually irregular amoeboid. The size of the inclusions does not exceed one thousandth of a millimetre. Often the series of inclusions bear indications of "unlacing". The phase ratio gas:liquid varies from 20:80 to 8:92. Homogenization takes place in the liquid phase in the interval from 300 to 150°C. Twenty repeated measurements of the temperatures of homogenization of sealed fluid inclusions have been made in sorensenite.

By means of the method of freezing (BAZAROV and MOTORINA, 1967) the liquid phase of the primary inclusions has been found to contain 21 per cent by weight of salts. NaCl is assumed to be predominant among the dissolved components.

**2. Tugtupite** Tugtupite is of widespread occurrence in Ilímaussaq. It is found in analcime and albite veins intersecting naujaite and augite syenite. The veins may be contiguous with veins of lujavrite occupying the same fracture zones and it is therefore believed that the albite-analcime veins have been formed from fluids squeezed out from the consolidating lujavrite magma (SØRENSEN, 1962, p. 174).

The tugtupite forms aggregates of equidimensional anhedra. There are often inclusions of chkalovite in these aggregates. The chkalovite is intersected by veinlets of granular tugtupite. It appears as if tugtupite is formed at the expense of chkalovite. The tugtupite is often enclosed in analcime or occurs in the marginal parts of analcime aggregates in albite.

The sample of tugtupite studied by us was collected in an albite-analcime vein intersecting augite syenite in the Kvanefjeld area. Further constituents are natrolite, sodalite, pyrochlore, neptunite, sphalerite, lithium-mica, epistolite, beryllite, chkalovite, *etc.*

A description of the mode of occurrence of tugtupite is in preparation (SØRENSEN and others, in preparation).

The amount of gas-liquid inclusions in the examined sample of tugtupite is small. Altogether 45 repeated determinations of the temperature of homogenization have been made. Two genetic types of inclusions
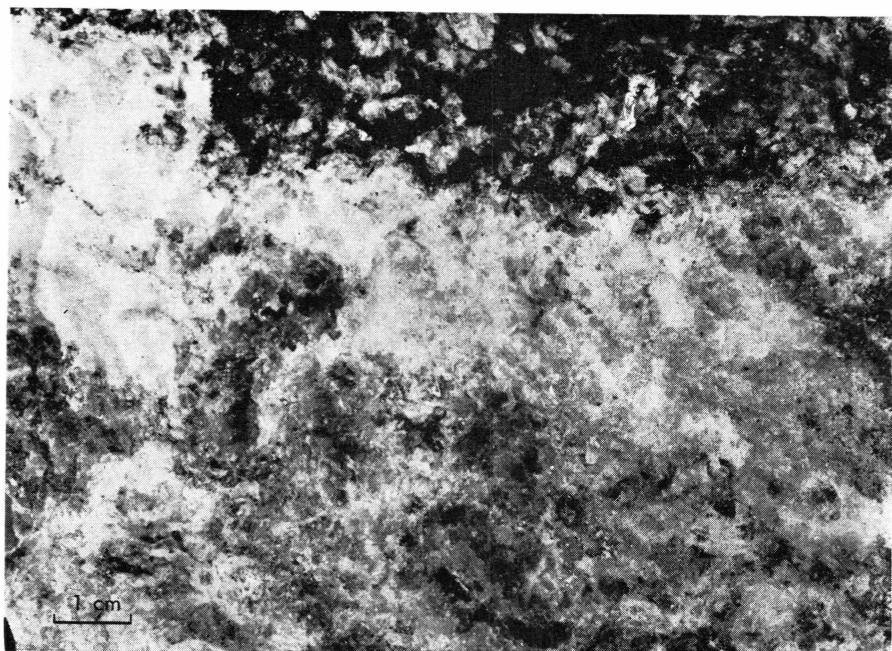
2*

Fig. 4. Vein of albitite with patches of tugtupite (dark shade) in augite syenite, Kvanefjeld. (*B. L. Nielsen phot.*).

are clearly defined: a. primary two-phase inclusions and b. secondary two-phase inclusions.

**a. The primary two-phase inclusions** are found as small groups (made up of 2–3 inclusions) irregularly distributed in the mineral. The inclusions are faceted (plate 1, fig. 4) and reach sizes of 0.005 mm. The phase ratio gas:liquid is approximately 40:60. Homogenization of the inclusions takes place in the liquid phase in the temperature interval from 440° to 460°C.

**b. The secondary inclusions** are confined to healed fractures. There are three generations of secondary inclusions which may be distinguished by their temperatures of homogenization, by morphology, and by phase composition.

The secondary inclusions of the first, most high-temperature generation have partially faceted shapes. Their size does not exceed one thousandth of a millimetre. The phase ratio gas:liquid is 15:85. The homogenization of these inclusions occurs in the liquid phase in a temperature interval from 310° to 350°C.

Secondary inclusions of the second generation are arranged in "chains", and bear clear indications of "unlacing" which took place when the content of the inclusions was homogeneous; this because their

Table 3. *The results of quantitative chemical analyses of the gas phase of individual inclusions (volume per cent).*

| Mineral | Temperature of homogenization °C | Diameter of bubble analysed, in mm | Increase of the size of the gas phase during opening of the vacuoles | $H_2S$, $SO_2$ $NH_3$ HCl HF | $CO_2$ | Heavy hydrocarbons | $O_2$ | CO | $H_2$ | $N_2$ + inert gases |
|---|---|---|---|---|---|---|---|---|---|---|
| 1. Chkalo- vite | 980 | 0.334 | 7.2 times | 0.0 | 23.5 | 0.0 | 0.0 | 0.0 | 0.0 | 76.5 |
| 2. — | 940 | 0.565 | 14.5 — | 0.0 | 37.2 | 0.0 | 0.0 | 0.0 | 0.0 | 62.8 |
| 3. — | Substan- tially gas | 0.442 | 14.75 — | 0.0 | 34.3 | 0.0 | 0.0 | 0.0 | 2.7 | 63.0 |
| 4. — | 420 | 0.304 | 10.9 — | 0.0 | 32.2 | 0.0 | 0.0 | 0.0 | 1.5 | 66.3 |
| 5. — | 860 | 0.570 | 11.4 — | 0.0 | 40.5 | 0.0 | 0.0 | 0.0 | 0.0 | 59.5 |
| 6. Tugtu- pite | 440 | 0.255 | 12.0 — | 7.55 | 88.6 | 0.0 | 0.0 | 0.0 | 1.7 | 2.15 |

homogenization occurs in a very narrow temperature interval from 240° to 260°C. The phase ratio gas:liquid is approximately 10:90.

The secondary inclusions of the third, most low-temperature generation are characterized partly by their temperature of homogenization, partly by a web-foot-like shape and by the complex relief of their inner surfaces (plate 1, fig. 5). They are furthermore of big size, reaching a few hundredths of a millimetre across. The phase ratio gas: liquid is equivalent to (3–5):(97–95). The homogenization of the inclusions occurs in the liquid phase within a very narrow temperature interval of 100° to 110°C.

It has not been possible to determine the composition of the liquid phase of the primary inclusions.

The gas phase of one primary inclusion homogenizing at 440°C was analysed by N. A. SHUGUROVA (see table 3). $CO_2$ is the predominant gas in this inclusion making up 88.6 volume per cent of the gas phase. $H_2S$, $SO_2$, $NH_3$, HCl and HF make up 7.55 volume per cent.

**3. Chkalovite.** This mineral occurs in late veins made up mainly of one or more of the minerals ussingite, albite and analcime. It is often partly replaced by tugtupite, beryllite, epididymite-eudidymite or spherobertrandite. The chkalovite always appears to be of early formation. The grains are often deformed being built up of sectors of slightly deviating orientation and being intersected by zones of granulation.

The chkalovite is generally in direct contact with ussingite while almost in all cases it is separated from the albite-analcime by zones or
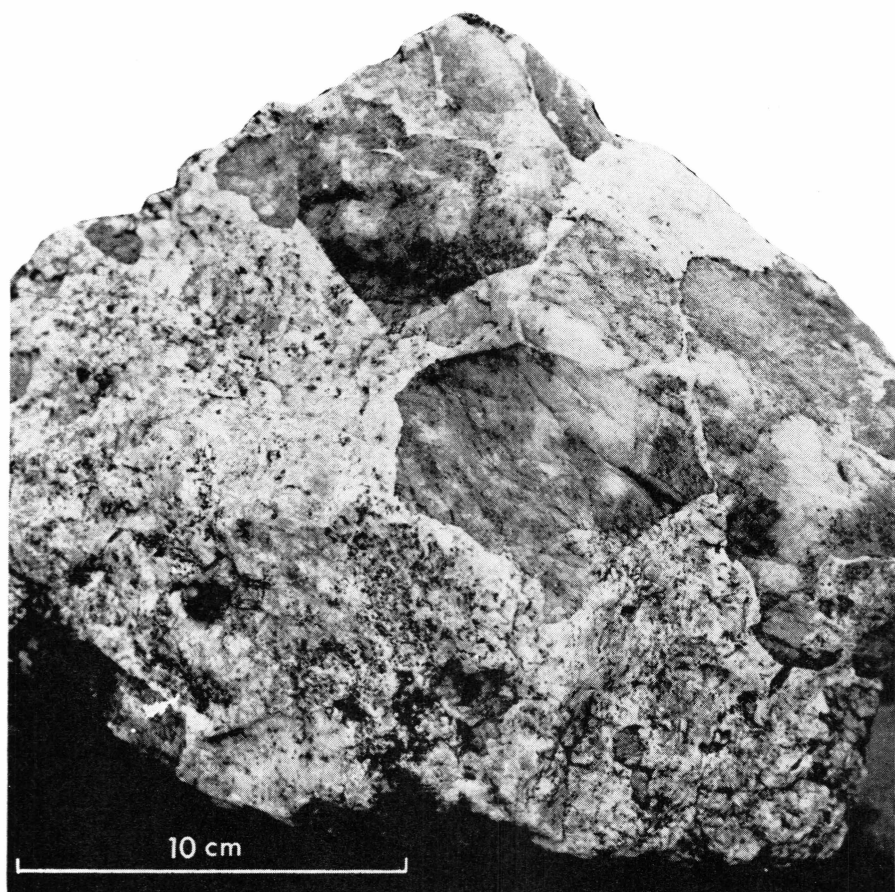
Fig. 5. Crystals of chkalovite enclosed in ussingite, the Taseq slope (*B. L. Nielsen* phot.).

films of tugtupite. The ussingite may be intersected by zones of fine-grained natrolite which are again cut by albititic material. All this indicates that the chkalovite-bearing veins may have had a complicated history of formation. As chkalovite invariably represents the first phase of formation the study of primary and secondary fluid inclusions in this mineral is of considerable interest.

The sample examined was collected in an ussingite vein on the Taseq slope in the northern part of the intrusion. These veins have marginal zones enriched in aegirine, yellow sodalite and steenstrupine and cores composed of ussingite, chkalovite, analcime, natrolite, epistolite, lithium-mica, sphalerite, molybdenite, chalcothallite, niobophyllite, rare tugtupite, *etc.* (*cf.* Semenov and others, 1967). The ussingite is intersected by veinlets of albite. Ussingite veinlets intersect the chkalovite crystals which may reach sizes of 20 cm.

The chkalovite-bearing veins intersect naujaite. It may be suggested that they represent totally replaced naujaite pegmatites, but it is most likely that they are formed from fluids expelled from the crystallizing lujavrite (SØRENSEN, 1962, p. 171).

Chkalovite was found to be a very suitable mineral for a complete mineral-thermometric analysis. It contains a great amount of two- and three-phase fluid inclusions which can be subdivided into two genetic groups: a. primary gas-liquid inclusions and b. secondary gas-liquid and essentially gas inclusions.

**a. The primary, most high-temperature, inclusions** are arranged parallel to the elongation of the mineral and are distributed comparatively evenly within a crystal. All are three-phase inclusions (plate 1, fig. 6, plate 2, figs. 1, 2, 3). The solid phase is represented by cubic or parallel-epipedal crystals of halite. Very often these "captive" crystals contain fluid inclusions made up substantially of gas. This gas phase is, apparently, the initial part of the gas phase released during heterogenization of the inclusion and captured during crystallization of halite within the inclusion (plate 1, fig. 6, plate 2, figs. 1, 3). The phase ratio gas: liquid + solid is approximately 50:50–60:40. In the experiments the solid phase is dissolved within the temperature interval from 330° to 360°C. The size of the fluid inclusions reaches some hundredths of a millimetre, but the inclusions suitable for experiments are those not larger than a thousandth of a millimetre because these remain sealed during heating. The group of high-temperature inclusions is characterized not only by high temperatures of homogenization but also by certain peculiarities which have never before been met with in mineral-thermometry. This peculiarity consists in the appearance during heating within the interval from 700° to 800°C of some kind of a new liquid phase which does not mix with the solution within the inclusion. During further heating this new phase very quickly decreases in size and disappears. Approximately within the same range of temperature (800°C), the cavities containing the fluid inclusions are subject to changes in shape and to an increase in size. The homogenization of the inclusions occurs during the liquid phase at temperatures varying from 980° to 860°C. At the moment of homogenization the volumes of the cavities containing the fluid inclusions are at their maximum. During gradual cooling the whole process is reversed. The volumes of the fluid inclusions reach their original size, but the shape of the inclusions becomes different.

We have previously come across changes of shape and an increase of size of vacuoles of fluid inclusions at temperatures close to the temperature of homogenization (700°–800°C) while examining inclusions in

nepheline (BAZAROVA and KOSTYUK, 1963; BAZAROVA, 1965), but in the latter case this process was irreversible.

Temperatures of homogenization of 980°–860°C are somewhat unusual for such a mineral as chkalovite. In this connection it is necessary to emphasize the exceptional ease, with which reactions take place in the solutions inside the fluid inclusions. When the inclusions leak and their content penetrates into fractures a rapid formation of new rows of inclusions and their not less rapid "lacing up" occur throughout the experiments. There are groups of inclusions with clear indications of "lacing up" (plate 2, figs. 4, 5) that could have resulted in the formation of inclusions with anomalous phase ratios and, hence, anomalous temperatures of homogenization. The homogenization of the "unlaced" inclusions with phase ratios most similar to those of the inclusions homogenized at 980°–860°C takes place at temperatures not exceeding 600°C. The primary high-temperature inclusions homogenize in groups of 3–5 or more at the same temperature and are accompanied by the abovementioned phenomena which were not observed in any of the inclusions homogenized at lower temperatures. The fact that homogenization resulting in the formation of a gas phase filling the fluid inclusions has not been observed also points against the possibility that the high-temperature inclusions were formed by "unlacing". It should at this point be noted that the chemical composition of the gas phase of the high-temperature inclusions is distinguished by the absence of hydrogen, $H_2$ (see table 3).

The temperatures of 980° to 860°C obtained for the crystallization of chkalovite by means of the examination of the high-temperature fluid inclusions in the mineral cannot be considered to be definitive at the present stage of the examination. Future experimental work on more extensive chkalovite material is needed in order to prove or disprove our preliminary results.

However, in spite of the unexpectedly high temperatures, no better results are available at the moment. It may therefore be suggested that chkalovite crystallized from a peculiar fluid-rich chloride-silicate melt, as has been suggested earlier by a number of authors (NIKOLAEV and DOLIVO-DOBROVOLSKII, 1961).

**b. The presumed secondary inclusions** may be divided into several genetic groups differing from each other in their temperatures of homogenization and in the compositions of their fluid phases:

i) **Three-phase inclusions** are very similar to those belonging to the primary group with regard to morphology, arrangement and phase composition (plate 3, figs. 1, 2). They differ from the latter only in somewhat different phase ratios gas:liquid + solid phase, which are approx-

imately (40–45):(60–55), and in the temperatures of homogenization and composition of the gas phase (table 3). The solid phase of these inclusions is represented by halite crystals which are dissolved within the interval of temperature of 190°–240°C. The NaCl concentration of these inclusions amounts to 28–32 weight per cent. Homogenization of the inclusions takes place in the liquid phase in the temperature range from 720° to 760°C. At temperatures close to homogenization no new phase appeared. The three-phase inclusions displaying these homogenization temperatures are found in small number.

ii) Two-phase gas-liquid inclusions with the phase ratio gas: liquid approximately 50:50–35:65 (plate 3, figs. 3, 4) are unevenly distributed in the crystals of chkalovite and are found in small groups of two or three. The homogenization of the inclusions takes place in the liquid phase in a range of temperatures between 550° and 600°C.

iii) The four-phase inclusions more often have an irregular or partially faceted shape and two crystalline apparently cubic phases (plate 3, fig. 5), one of which dissolves at 160°C (apparently KCl) and the other at 330°–350°C (NaCl). Gas makes up 25–30 per cent of the volume of these inclusions. Homogenization of the inclusions takes place in the liquid phase within the range of temperatures from 500° to 530°C. Within this interval several three-phase inclusions have been homogenized, the solid phase of which was dissolved at 210°C.

iv) These are the three-phase inclusions which homogenize within a narrow temperature interval from 400° to 420°C (plate 3, fig. 6). The phase ratio gas:liquid + solid phase is (20–25):(80–75).

v) Low-temperature gas-liquid inclusions confined to healed fractures (plate 4, fig. 1). Their homogenization takes place within the temperature interval 140°–160°C.

vi) Fluid inclusions dominated by a gas phase and confined to fractures (plate 4, figs. 2, 3). The liquid within these inclusions is revealed only during cooling.

Altogether over 250 measurements of the temperature of homogenization of sealed fluid inclusions in chkalovite have been undertaken. More than 50 per cent of these measurements fell on the high-temperature inclusions (980°–860°C).

The results of the measurements of temperatures of homogenization of fluid inclusions in chkalovite, tugtupite and sorensenite are presented in table 2. The results of chemical analyses of the gas phase of individual inclusions are presented in table 3. The analyses of the gas-phase were undertaken by N. A. SHUGUROVA.

It should be mentioned that the data presented in table 3 represent the composition of the gas phase of individual inclusions. The values

indicate the part of the volume of the gas phase of these inclusions made up of various gaseous components. The data do not reflect the gas concentration in the homogeneous fluids contained in each fluid inclusion. The composition of the gases held in solution can only be determined when the volume of an inclusion is known.

The chemical composition and the concentration of the dominant salts in the liquid phase of the three phase inclusions in chkalovite were determined by L. SH. BAZAROV by means of freezing of the inclusions (*cf.* p. 10). The identification of a predominant salt ("captive" crystal) was carried out by means of the method worked out by BAZAROV and MOTORINA (1967). The procedure for the examination consists of thorough studies of the behaviour, properties and phase transformations of the solutions trapped in the vacuoles at minus-temperatures. The physical-chemical diagrams which present the data obtained are then compared with the properties of various salt systems.

From this examination it may be concluded that the solid phase ("captive" crystals) in the high-temperature inclusions is represented by NaCl. The concentration of the other salts dissolved in the solutions, which reduce the temperature of true eutectic crystallization of the solutions (towards $-46°$C), is low because these assumed salts (possibly $CaCl_2$) do not produce a crystalline phase during the eutectic crystallization. The approximate concentration of NaCl in the solutions of the inclusions (the crystals of NaCl are dissolved at $330-360°$C), as calculated from the diagram of the two-component system $NaCl-H_2O$ (STYRIKO-VICH and KHAIBULLIN, 1956) is equivalent to 40–44 weight per cent. The pressure during the formation of the fluid inclusions may be estimated by means of the methods worked out by BAKUMENKO, DOLGOV and BAZAROV (1965). The pressure at the moment of homogenization of an inclusion is estimated to be higher than 1000 atm.

# DISCUSSION OF THE MINERAL-THERMOMETRIC ANALYSIS OF SORENSENITE, TUGTUPITE AND CHKALOVITE

## 1. Main results of the preliminary examination of the fluid inclusions

**a. Sorensenite** was formed at temperatures of 420°–400°C from strongly saline hydrothermal solutions containing about 21 weight per cent salts, mainly NaCl. The pressure at the temperature of homogenization is estimated to be 280 atm. (*cf.* STYRIKOVICH and KHAIBULLIN, 1956). The phase ratio gas:liquid is about 30:70 in the primary inclusions.

Secondary inclusions gave a temperature of homogenization of 300°–150°C.

**b. Tugtupite** crystallized at temperatures not lower than 460°–440°C. The phase ratio gas:liquid is about 40:60 in the primary inclusions. The gas phase in the only primary inclusion examined was strongly enriched in $CO_2$ (88.6 vol. per cent), while ($H_2S + SO_2 + NH_3 + HCl + HF$), $H_2$, and $N_2$ + inert gases were of subordinate importance (see table 3).

The secondary inclusions homogenized in the temperature intervals 350°–310°C (faceted vacuoles), 260°–240°C (bead-like strings of vacuoles) and 110°–100°C. Thus the second generations of fluid inclusions were formed by healing of fractures.

**c. Chkalovite** appears to have crystallized from a water-rich chloride-silicate liquid phase at temperatures of 980°–860°C and at pressures exceeding 1000 atm (see p. 24 and *cf.* BAKUMENKO and others, 1965; SOBOLEV and others, 1967). The phase ratio gas:liquid is about 50:50 to 60:40. The presence of crystals of halite, *etc.* at room temperature indicates a high concentration of salts in the liquid, according to the present examination 44 weight per cent. The gas phase of these high temperature inclusions is dominated by $N_2$ + inert gases and $CO_2$, while $H_2$ is absent.

There are several generations of secondary inclusions. Three generations have homogenization temperatures between 760° and 500°C, one

generation homogenizes at 420°–400°C and two at temperatures below 160°C. The gas phase of the secondary inclusions is dominated by $N_2 +$ inert gases and by $CO_2$. $H_2$ may be a minor component.

**d.** It is a remarkable fact that all the inclusions studied, even those homogenizing at 600°–980°C, are filled by the liquid phase at the temperature of homogenization. This indicates that the liquids were so saline (and the pressure so high) that the liquids did not show critical phenomena.

**e.** In a restricted interval of temperatures (800°–700°C) there are two immiscible liquid phases in the high temperature fluid inclusions in chkalovite. Within the same range of temperatures the vacuoles are subject to changes of size and shape indicating a pronounced solution of material from the walls of the cavities. This may indicate that the chkalovite was formed from a strongly saline liquid enriched in sodium-aluminium-silicates and volatiles. This liquid (melt?) split up into two liquids during cooling, the one a silicate-rich phase, the other an aqueous solution rich in alkali halides. The silicate-rich phase in the fluid inclusions was partly used up by deposition of a film of chkalovite, etc. on the walls of the cavities.

## 2. The temperature of formation of the rocks of Ilímaussaq

As mentioned above Piotrowski and Edgar (1969) have examined a few rocks from Ilímaussaq experimentally. They found that at 1030 bars water pressure the liquidus temperatures for naujaite and green lujavrite are 910°C and 885°C respectively, and that the solidus temperatures of these rocks at the same pressure are about 430°C. Thus these rocks are characterized by very long melting intervals.

The fact that the lujavrites contain pure microcline in association with pure albite indicate a low temperature of formation (Ussing, 1912, p. 160 and Sørensen, 1962, p. 180); perhaps the final temperature of consolidation was as low as 400°C. Microcline and albite occur as discrete crystals indicating that both minerals crystallized as separate phases from the lujavrite magma. In contrast the feldspar of the naujaite is a microcline microperthite which may well represent the unmixing of a homogeneous feldspar as a result of the long interval of consolidation.

## 3. Conclusions

The hydrothermal veins of Ilímaussaq are most probably genetically connected with the consolidation of the lujavrite magma (Sørensen, 1962). They may have been formed from fluids squeezed out during the

consolidation of the lujavrite. The texture of this rock indicates that it crystallized during a period of deformation. The lujavrites are the most fine-grained agpaitic nepheline syenites of Ilímaussaq indicating a rather short period of crystallization. This may be a result of intermittent expulsion of fluids during the crystallization. The temperatures of homogenization of sorensenite and tugtupite are in excellent agreement with the temperatures obtained experimentally and from mineralogical data, that is temperatures of 400°–460°C. The association of sorensenite and tugtupite with analcime, and the late formation of tugtupite in most of the veins in which this mineral has been found, are also indications of rather low temperatures of formation. Thus the fluids responsible for the formation of sorensenite and tugtupite may be considered to have been residual liquids genetically connected with the lujavrite magmas.

As to the chkalovite the high temperature of homogenization of the primary and some secondary fluid inclusions appears to be incredibly high. The great number of measurements shows, however, that these extraordinarily high temperatures are not due to experimental errors.

As mentioned above, chkalovite is the earliest or one of the earliest minerals in the veins in which it occurs. It forms crystals of pegmatitic dimensions which might be regarded as remnants of naujaite pegmatites that have otherwise been totally replaced. Chkalovite is, however, apparently a rare mineral in naujaite pegmatites and it is furthermore most unlikely that a great number of apparently pneumatolytic-hydrothermal veins should replace naujaite pegmatites selectively.

The next possibility to consider is that the chkalovite was formed from fluids expelled from the lujavrite magma at approximately liquidus temperatures. These fluids as mentioned above, have been highly saline silicate liquids or melts. The separation of such fluids at liquidus conditions necessitates an interplay of immiscibility relations between the lujavrite magma and sodium silicate-rich liquids. It appears to be rather unlikely that such liquids of early formation could be so enriched in beryllium that chkalovite could crystallize as an early phase.

ROEDDER and COOMBS (1967) have examined inclusions in peralkaline granites from Ascension Island and have demonstrated that immiscibility played a role during the crystallization of these granites. The multiphase inclusions observed by them, e.g. those containing silicate glass, a large halite crystal, a saturated aqueous solution and a gas bubble, have not been observed in the present study. They also found evidence of boiling during the trapping of the fluid phase, a phenomenon not observed in the present study. They found homogenization temperatures of about 600°C (not corrected for pressure).

The phase relations of the fluid inclusions excludes a pneumatolytic origin of the chkalovite and also formation from a boiling liquid.

It is thus hard to understand that the chkalovite could have crystallized at such high temperatures as indicated by the homogenization experiments. It is to be hoped that the continued studies may bring the answer to this problem.

Villiaumite (NaF) is of widespread occurrence in Ilímaussaq. Its presence has not been proved in the analyzed primary fluid inclusions. Villiaumite, is, however, a late mineral and may be present in low temperature secondary inclusions for which analytical data are not yet available. This is in accordance with the results of an examination of fluid inclusions in nephelines from Lovozero (IKORSKY, 1966).

I. A. PETERSILIE (paper in preparation) has found that the gases collected at room temperature from crushed naujaite and lujavrite are enriched in hydrocarbons, just as the agpaitic rocks from Lovozero and Khibina (PETERSILIE, 1963). The rocks of Khibina and Lovozero, which have been albitized, have low contents of hydrocarbons. This indicates that the hydrocarbons are not related to the pneumatolytic-hydrothermal period of mineralization (Petersilie, op. cit.).

The hydrocarbons appear to be restricted to pores and micro-fissures in the orthomagmatic rocks. The high temperature primary fluid inclusions in nepheline from the Lovozero urtites are rich in $CO_2$ (about 98 volume per cent), while hydrocarbons are predominant in secondary inclusions homogenizing at 600–400° C (BAZAROVA, 1969).

The high contents of $N_2$ and inert gases in the chkalovite and nepheline are hard to explain on the basis of the available data. It is also too early to discuss the high contents of $CO_2$ in nepheline and tugtupite and the low content of this compound in chkalovite. A detailed study of the fluid inclusions in a number of minerals from Ilímaussaq is in preparation.

# REFERENCES

ANDERSEN, S. (1967) On beryllite and bertrandite from the Ilímaussaq alkaline intrusion, South Greenland. Meddr Grønland Bd. 181, Nr. 4$^{II}$, 11–27.

BAKUMENKO, I. T., DOLGOV, YU. A. and BAZAROV, L. SH. (1965) Method of determination of pressure in inclusions by means of joint application of homogenisation and cryometry (In Russian). Thesis from report presented at the II All-Union conference on geothermo-barometry. Novosibirsk 1965.

BAZAROV, L. SH. (1966) The equipment for freezing of fluid inclusions in minerals (In Russian). Materials on genetic and experimental mineralogy, v. IV, Novosibirsk.

BAZAROV, L. SH. and MOTORINA, I. V. (1967) Determination of composition of solutions of individual multiphase fluid inclusions by the freezing method (In Russian). Dokl. AN, U.S.S.R., v. 176, no. 6.

BAZAROVA, T. YU. (1965) Mineralo-thermometric examinations of inclusions in minerals of some nepheline rocks (In Russian). Dokl. AN, U.S.S.R., v. 161, no. 4.

— (1969) Thermodynamic conditions of formation of some nepheline-bearing rocks. (in Russian). Ed. "Nauka".

BAZAROVA (KERKIS) T. YU. and KOSTYUK, V. P. (1963) A mineralo-thermometric study of nepheline from Botogol (East Sayan) (In Russian). Dokl. AN, USSR, v. 150, no. 5.

BONDAM, J. and FERGUSON, J. (1962) An occurrence of villiaumite in the Ilímaussaq intrusion, South Greenland. Meddr Grønland Bd. 172, Nr. 2, 1–12.

DOLGOV, YU. A. and BAZAROV, L. SH. (1965) A chamber for examination of inclusions of mineral-forming solution and melts at high temperatures (In Russian). Sbornik Mineralogic thermometry and barometry, v. I, Moscow. Ed. "Nauka".

DOLGOV, YU. A. and SHUGUROVA, N. A. (1966) Examination of individual gas inclusions (In Russian). Materials on genetic and experimental mineralogy. v. IV, Novosibirsk.

ERMAKOV, N. P. (1950) Examinations of the mineral-forming solutions, Kharkov. (English translation): Research on the nature of mineral-forming solutions. International Series of Monographs on Earth Sciences, vol. 22, Pergamon Press.

FERGUSON, J. (1964) Geology of the Ilímaussaq alkaline intrusion, South Greenland. Part I. Description of map and structure. Meddr Grønland Bd. 172, Nr. 4, 1–81.

IKORSKY, S. W. (1966) Inclusions of villiaumite and their connection with organic matter in the rock-forming minerals of the Khibina Intrusion (In Russian). Geochemistry, no. 8.

KOSTYUK, V. P. and BAZAROVA, T. YU. (1966) Petrology of the alkaline rocks of the eastern part of East Sayan. Ed. "Nauka".

LEMMLEIN, G. G. and KLEVTSOV, P. V. (1956) The effect of concentration upon the temperature of homogenisation of systems consisting of aqueous salt solutions (In Russian). Notes of the All-Union Min. Soc., Part 85, 3.

NIKOLAEV, V. A. and DOLIVO-DOBROVOLSKII, V. V. (1961) The principles of a theory of the processes of magmatism and metamorphism (In Russian). Moscow, Ed. "Gosgeolteknizdat".

PANINA, L. I. (1966) Certain data on the temperature condition of formation of the Synnur alkaline massif (In Russian). Dokl. AN, U.S.S.R., v. 170, no. 6.

PETERSILIE, I. A. (1963) Organic matter in eruptive and metamorphic rocks of Kola Peninsula. In: VINOGRADOV, A. P., ed.: The chemistry of the earth's crust.

PIOTROWSKI, J. M. and EDGAR, A. D. (1969) Melting relations of undersaturated alkaline rocks from South Greenland, compared to those of Africa and Canada. Meddr Grønland, Bd. 181, Nr. 9, 1–62.

ROEDDER, E. and COOMBS, D. S. (1967) Immiscibility in granitic melts, indicated by fluid inclusions in ejected granitic blocks from Ascension Island. J. Petrol. v. 8, 417–451.

SEMENOV, E. I., GERASSIMOVSKY, V. I., MAKSIMOVA, N. V., ANDERSEN, S. and PE-TERSEN, O. V. (1965) Sorensenite, a new sodium-beryllium-tin-silicate from the Ilímaussaq intrusion, South Greenland. Meddr Grønland, Bd. 181, Nr. 1, 1–19.

SEMENOV, E. I., SØRENSEN, H., BESSMERTNAJA, M. S. and NOVOROSSOVA, L. E. (1967) Chalcothallite—a new sulphide of thallium and copper from the Ilímaussaq alkaline intrusion, South Greenland. Meddr Grønland, Bd. 181, Nr. 5[II], 13–26.

SOBOLEV, V. S., KOSTYUK, V. P., BAZAROVA, T. YU. and BAZAROV, L. SH. (1967) Inclusions of melts in phenocrysts of nepheline basalts (In Russian). Dokl. AN, U.S.S.R., v. 173, no. 2.

SØRENSEN, H. (1958) The Ilímaussaq batholith, a review and discussion. Meddr Grønland, Bd. 162, Nr. 3, 1–48.

— (1962) On the occurrence of steenstrupine in the Ilímaussaq massif, Southwest Greenland. Meddr Grønland, Bd. 167, Nr. 1, 1–251.

— (1967) On the history of exploration of the Ilímaussaq alkaline intrusion, South Greenland. Meddr Grønland, Bd. 181, Nr. 3, 1–33.

SØRENSEN, H., DANØ, M. and PETERSEN, O. V. (in preparation). Tugtupite from the Ilímaussaq alkaline intrusion, South Greenland. Meddr Grønland.

SØRENSEN, H., HANSEN, J. and BONDESEN, E. (1969) Preliminary account of the geology of the Kvanefjeld area of the Ilímaussaq intrusion, South Greenland. Rapp. Grønlands geol. Unders. no. 18.

STYRIKOVICH, M. A. and KHAIBULLIN, I. KH. (1956) Phase diagrams of the systems: $NaCl–H_2O$; $Na_2SO_4–H_2O$; $CaSO_4–H_2O$; $SiO_2–H_2O$ (In Russian). Dokl. AN, U.S.S.R., 109, 962–965.

USSING, N. V. (1898) Mineralogisk-petrografiske Undersøgelser af grønlandske Nefelinsyeniter og beslægtede Bjergarter. Medd. Grønland, 14, 1, 1–220.

— 1912: Geology of the country around Julianehaab, Greenland. Meddr Grønland, Bd. 38, 1–376.

PLATES

## Plate 1

Fig. 1. Primary multiphase inclusion in nepheline from naujaite. × 400. Temperature of homogenization 1040°C.

— 2. Secondary inclusions in nepheline from naujaite. × 400.

— 3. Primary inclusion in sorensenite. Temperature of homogenization 400°C. × 400.

— 4. Primary inclusion in tugtupite. Temperature of homogenization 420°C. × 400.

— 5. Secondary (the most low-temperature) inclusions in tugtupite. Temperature of homogenization 100°C. × 400.

— 6. High temperature inclusion in chkalovite. × 400. Temperature of homogenization 860°C.

Fig. 1



Fig. 2
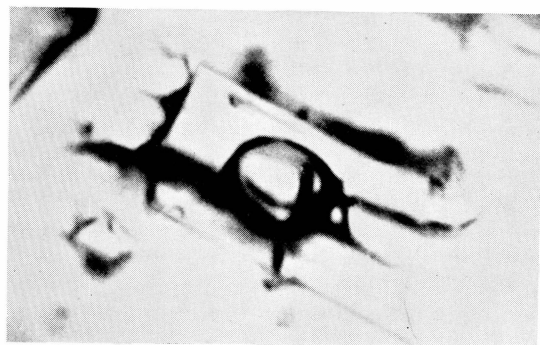


Fig. 3
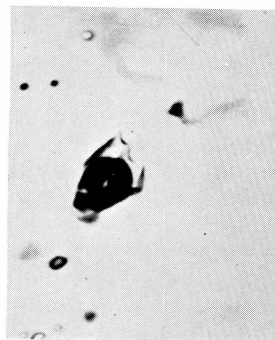


Fig. 4



Fig. 5



Fig. 6

## Plate 2

Fig. 1. High temperature inclusions in chkalovite. × 400. Temperature of homogenization 980°C.

— 2. High temperature inclusion in chkalovite. × 400. Temperature of homogenization 910°C.

— 3. High temperature inclusion in chkalovite. × 400. Temperature of homogenization 980°C.

— 4. Groups of inclusions in chkalovite with indications of "unlacing". × 400.

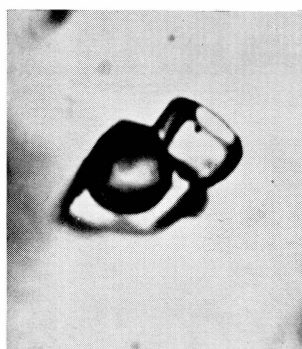— 5. Groups of inclusions in chkalovite with indications of "unlacing". × 400.

Fig. 1

Fig. 2
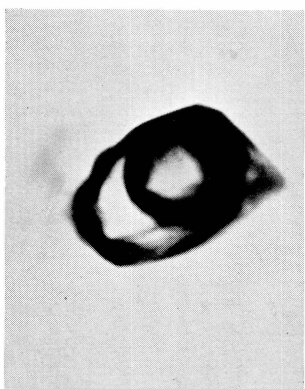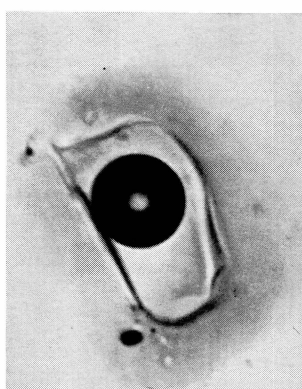
Fig. 3
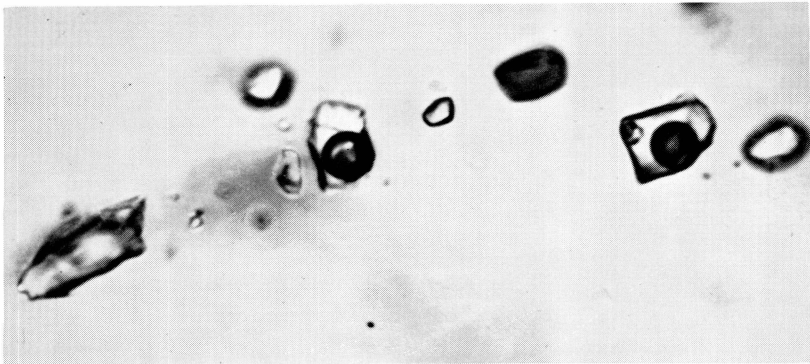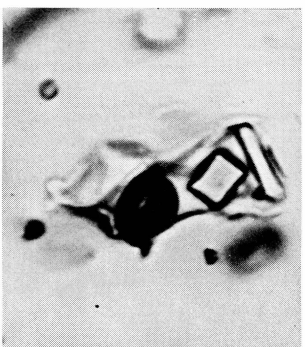


Fig. 4
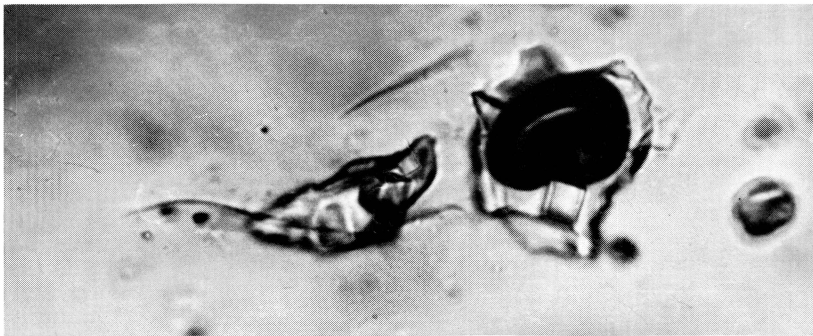


Fig. 5

## Plate 3

Fig. 1. Secondary three-phase inclusion in chkalovite. × 400. Temperature of homo-
genization 760°C.
— 2. Secondary three-phase inclusion in chkalovite. × 400. Temperature of homo-
genization 760°C.
— 3. Secondary two-phase inclusion in chkalovite. × 400. Temperature of homo-
genization 600°C.
— 4. Secondary two-phase inclusion in chkalovite. × 400. Temperature of homo-
genization 550°C.
— 5. Secondary four-phase inclusion in chkalovite. × 400. Temperature of homo-
genization 530°C.
— 6. Secondary three-phase inclusion in chkalovite. × 400. Temperature of homo-
genization 420°C.

Fig. 1



Fig. 2



Fig. 3



Fig. 4



Fig. 5



Fig. 6

## Plate 4

Fig. 1. Secondary three-phase inclusion in chkalovite. × 400. Temperature of homo-
genization 160°C.
— 2. Secondary substantially gas-inclusions in chkalovite. × 400.
— 3. Secondary substantially gas-inclusions in chkalovite. × 400.

Fig. 1



Fig. 2
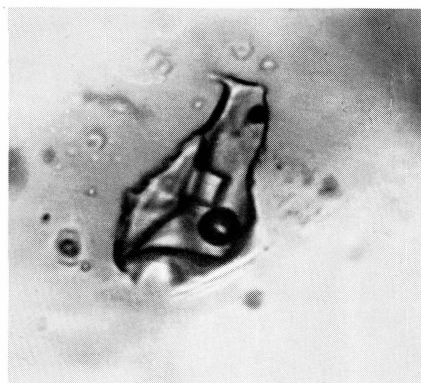


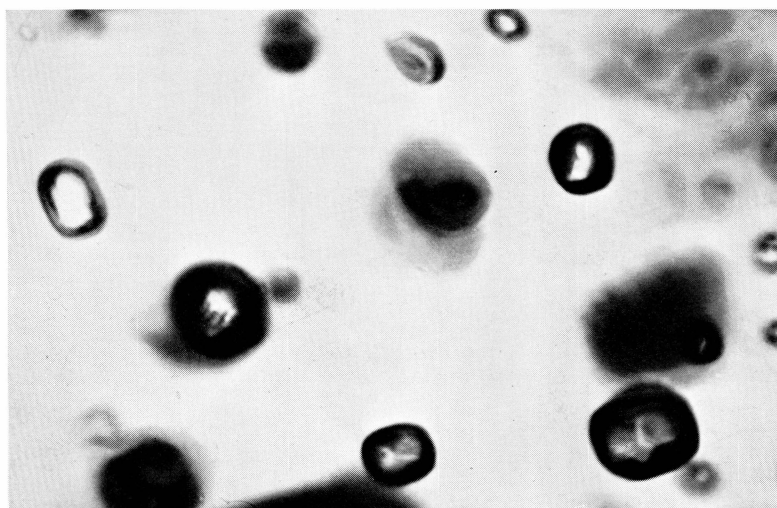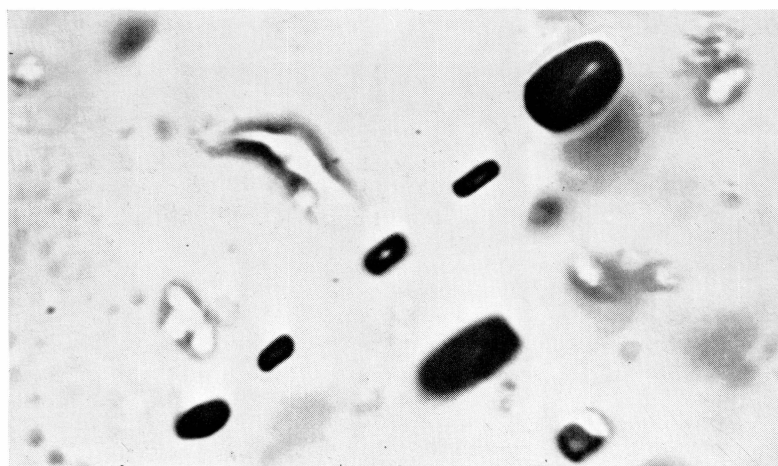Fig. 3