Topaz, prosopite and closing stages of formation of the Ivigtut cryolite deposit, South Greenland

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The evolution of the cryolite deposit at Ivigtut is divided into three stages. This work deals with the last two.

Siderite-cryolite ($2\frac{1}{2}$ 10^6 tons) followed by the body of pure, white cryolite accompanied by chiolite ($1/2$ 10^6 tons) crystallized in Stage 1. An abrupt change in conditions led to Stage 2 in which the fluorite zone and the fluorite-cryolite (1 10^6 tons) formed. Finally, in Stage 3, fluids left from Stage 2 in fissures and cavities, dissolving cryolite gave rise to thomsenolite and other secondary minerals, (0.08 10^6 tons).

The cryptocrystalline topaz, emplaced in breccias and vein breccias with fluidized emplacement and penetrating cryolite along, unusual, cleavage planes, indicates that the transition from Stage 1 to Stage 2 was marked by extensive gas-driven explosions related to a Ca-F-rich residue. During these events colloform fluorite precipitated and formed with topaz the fluorite zone in the deeper part of the deposit; above, mechanically admixed cryolite gave rise to the fluorite-cryolite.

Concentrations of the minor elements Mg, K and Sr-Ba resulted in formation of weberite, spherulitic K-mica, jarlite and other Sr-Ba minerals in the last part of Stage 2. Chiolite broke down but cryolite remained stable during most of Stage 2.

Fluids left after Stage 2 dissolved cryolite and thomsenolite, ralstonite and other secondary Ca-fluorides formed. In an early phase of Stage 3 limited explosions precipitated prosopite in fluidized emplaced vein breccias similar to those carrying topaz. These events also led to the formation of the peculiar stalactitic or agate-like fluorite where the explosions hit cavities with solutions rich in Ca.

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Introduction

The cryolite deposit at Ivigtut (now Ivittuut) in S-Greenland consisted in its upper parts of cryolite with siderite, quartz and sulphides. It is the siderite-cryolite (Pauly 1960). In its lower and western part fluorite, cryptocrystalline topaz, weberite, sperulitic K-mica, jarlite and traces of pyrite constituted the impurities in the cryolite; this material is called fluorite-cryolite. The spherulitic K-mica which is green, is in the following mentioned by its local name "ivigtite" in order to distinguish it from well crystallized K-mica which is present in small amounts. Between the two types of cryolite occurred a body of pure, white cryolite accompanied by some chiolite. Under the fluorite-cryolite was the fluorite zone which was a cryolite-free mass composed of fluorite, topaz, weberite, "ivigtite", jarlite and traces of pyrite, in fact the same minerals found as impurities in

fluorite-cryolite. The mutual arrangement of these units in the cryolite deposit is illustrated in a cross section of the deposit in Fig. 1, see also Pauly (1986a, b).

Within the deposit siderite-cryolite followed by the pure, white cryolite with chiolite formed first in what can be termed Stage 1. The fluorite-carrying units consolidated next, in Stage 2. Fluids emerging from these processes gave rise to secondary minerals formed at the expense of cryolite (thomsenolite, pachnolite, ralstonite, gearksutite and others) in Stage 3 and represent the final activity in the formation of the deposit. Crystal-lined cavities are characteristic for Stage 3. They appeared in small amounts with the minerals formed late in Stage 2. Siderite-cryolite and the pure, white cryolite did not carry cavities. The mineral topaz only appeared in Stage 2. The occurrence of prosopite marks the transition from Stage 2 to Stage 3. The appearances of these two minerals and their relations to other minerals in the deposit are described in the following because

they most clearly monitor the conditions and the timing of events during the closing stages of the development of the cryolite deposit.

Topaz, properties and occurrence

Topaz, which is an important constituent in fluorite-cryolite (nearly 5% of the total mass) and in the fluorite zone (close to 30% of the mass), is cryptocrystalline. In thin sections the dense masses of topaz look like flint when viewed between crossed polars. Distinct spherulitic aggregates as illustrated in Bøggild (1953) are rare. Where fluorite borders on topaz masses, micron-wide crystals of topaz may be seen penetrating 50 to 100 μm into the fluorite. Radiating aggregates of tiny topaz crystals have also been observed in cavities (Bøggild 1953).

The dense, cryptocrystalline topaz masses are often as white as chalk but they can take on greenish or purple hues where they contain disseminations of "ivigtite" or fluorite.

Topaz formed veins – or rather fissure fillings – usually millimetre thick sometimes up to decimetre thick and metre long. According to an unpublished report by R. Bøgvad in 1937 a topaz vein was observed in the west-wall two metres above the floor of the quarry and this vein could be followed over a distance of more than 50 metres. Accumulations of topaz, several decimetres in cross section, were now and then encountered in the quarry notably in the lower parts of the fluorite-cryolite where it bordered against the fluorite zone.

Thin sections of a white topaz vein, 7 cm across, were made in order to ascertain its purity. Fig. 2 shows that the macroscopically homogeneous topaz vein is composed of fragments of crust-like topaz masses cemented by topaz. Microprobe analyses failed to detect any other mineral than the cryptocrystalline, flint-like topaz; only a variation in the density of pores or microscopic holes was seen. Viewed in an ordinary microscope the fragments appear strongly pigmented whereas the topaz between them is rather transparent. Opaque microscopy showed the pigment to be mainly minute pores or holes rarely above 2–5 μm across. Light scattered in the micron-sized pores makes them appear as an opaque pigment in an ordinary microscope. The thin sections placed on a sheet of black, glossy paper, Fig. 2, appears white where the minute pores scatter the light. The rather clear topaz between the fragments allows the black background to be seen.

A prism, 2.8 cm^3, cut from the sample was found to have d = 3.37 g/cm^3 (micrometre screw measurements). Determinations in a gas-pycnometer gave d = 3.42. The white, dense topaz has been found to have the following lattice constants: a = 4.0497 ±0.0003Å, b = 8.7979 ±0.0007 and c = 8.4091 ±0.0005 which give d_x = 3.553. Taken together these determinations seem to indicate a
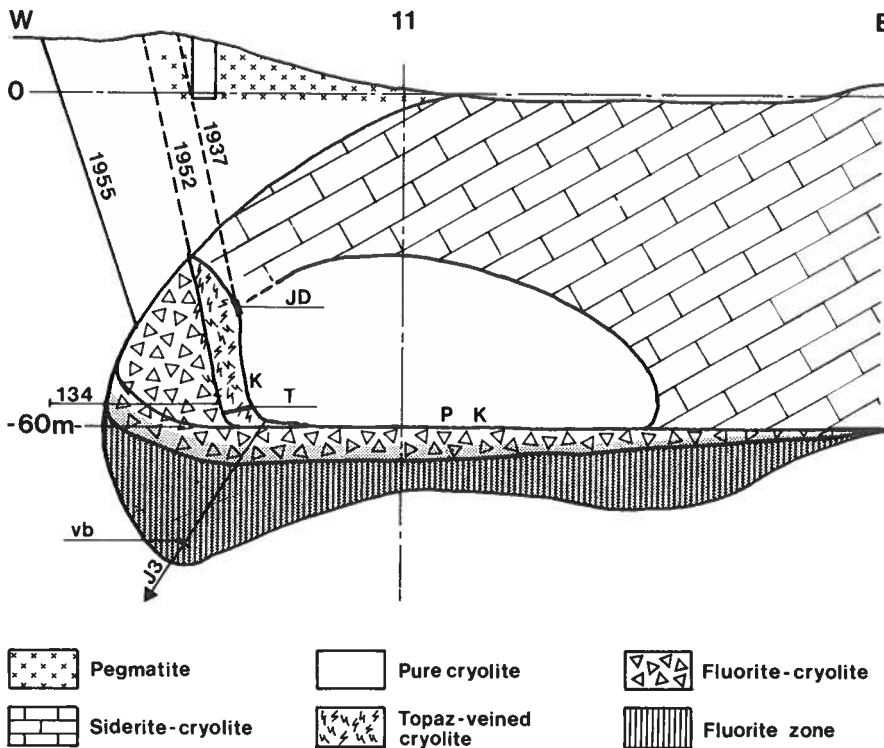
Fig. 1. E–W section through the western part of the Ivigtut cryolite deposit. Positions of the west wall of the quarry in the years 1937, 1952 and 1955 are marked. JD indicates the position of the "jarlite-druse" which represented decimetre thich segregations of jarlite and associated minerals stretching about 7 m on both sides of this section. T marks the position of the decimetre-thick topaz vein, more than 50 m long, observed in 1937–51. K represents locations for chiolite; vb marks position of a vein breccia seen in the core from the diamond drilling J₃. Prosopite was observed in cavernous masses 30 m south of the point marked P. The shaded lower part of the fluorite-cryolite plus the fluorite zone represents in this section the cavity containing the Ca-Al-F-rich residue left over after the consolidation of the products of Stage 1 (siderite-cryolite and the pure, white cryolite accompanied by chiolite).

Legend:
- Pegmatite
- Siderite-cryolite
- Pure cryolite
- Topaz-veined cryolite
- Fluorite-cryolite
- Fluorite zone

Fig. 2. Two thin sections across a white, dense vein of topaz. The sections cover the full width, 5.5 cm, of the vein apart from a 1.5 mm gap between them. They have been photographed on black paper. This reveals that the pure, cryptocrystalline topaz of the vein consists of broken-up crusts of topaz cemented by topaz. Densely spaced, micron-sized pores render part of the topaz white and opaque; the less porous, translucent topaz allows the black background to show through. Cryolite and fluorite with thin strings of topaz constitute the dark area of the upper section.
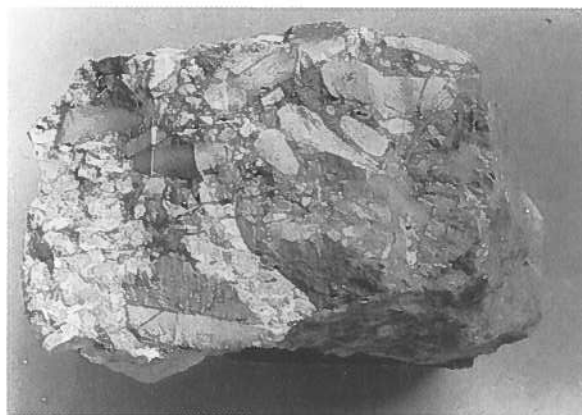
Fig. 3. Sample, 12 cm long, of topaz vein showing topaz crusts brecciated and cemented by topaz containing finely dispersed purple fluorite.

porosity of the white, dense topaz close to 4% and possibly further 1% pores inaccessible to the gas.

The brecciation of the topaz mass indicates that the vein formed through repeated injections of "fluids" which deposited the cryptocrystalline mineral, breaking up earlier formed crusts, recementing them and so on.

Coloured samples of massive topaz clearly show the multiple brecciations because the successive depositions of topaz contained varying concentrations of purple fluorite. Fig. 3 illustrates such a breccia where the cementing topaz contains fluorite as a pigment. Closer inspection of cut surfaces through the sample shows brecciation within the larger fragments. Coloured samples of topaz may also appear as stratified, very fine grained "sediments"; millimetre to centimetre thick layers are found to consist of elongated, pebble-like topaz cemented by topaz of a slightly different shade.
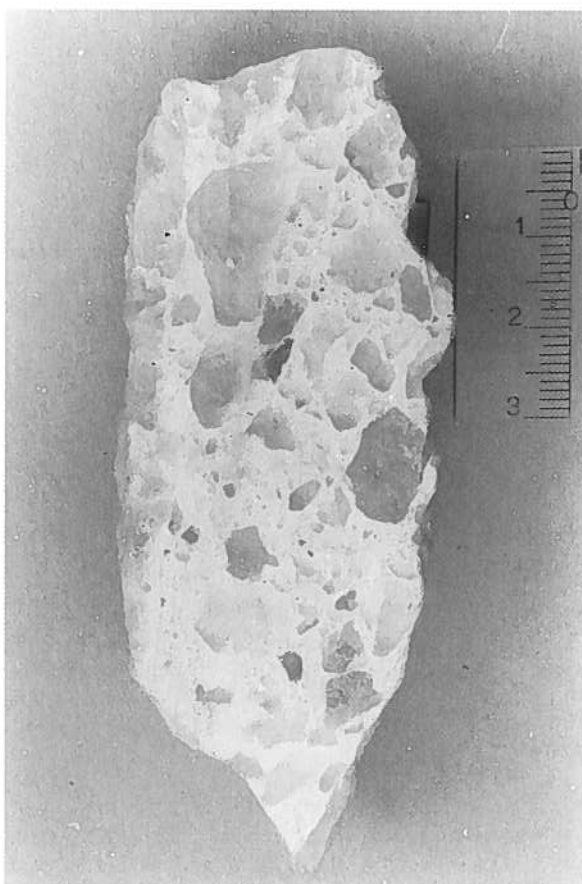
Fig. 4. Sample of vein breccia with centimetre-sized fragments of cryolite. Scale in centimetre.
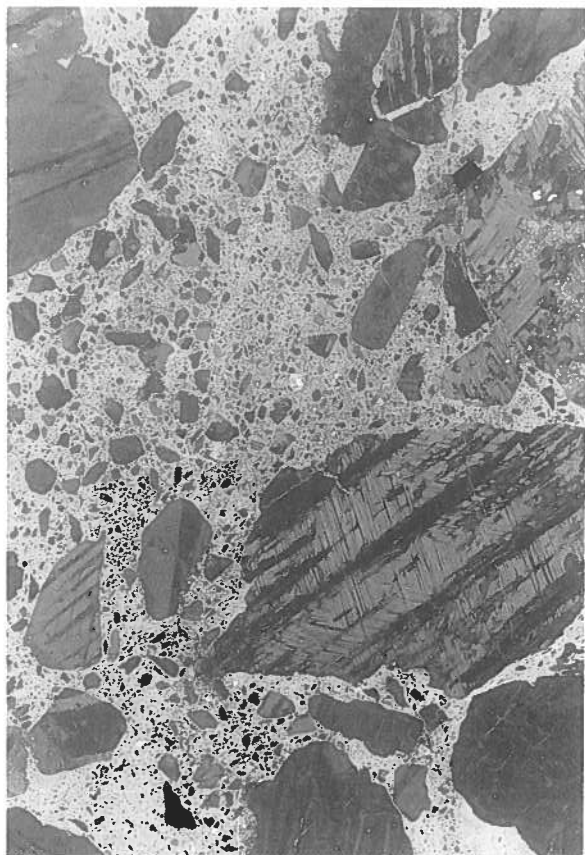
Fig. 5. Thin section, crossed polars, width of picture 1.14 cm. It is cut from the vein breccia shown in Fig. 4. The centimetre-sized fragments of cryolite are embedded in a matrix of fine grained cryolite with grain sizes down to 5–10 µm. Topaz is present between the densely packed cryolite grains. Sharp edged grains of cryolite are seen with systems of polysynthetic twin lamellae.

Fig. 6. Section of a drill core, 5 cm in diameter, from the fluorite zone, diamond drilling J₃, position marked vb on Fig. 1. Colloform fluorite with some weberite transected by a vein breccia with topaz between fragments of fluorite and a few grains of weberite.

Topaz in breccias and vein breccias

Coarse breccias with fragments of cryolite and/or fluorite cemented by the dense topaz were frequently found in topaz-rich parts of the deposit. Fluorite blocks with straight borders to the surrounding topaz were found to be cleavage fragments of decimetre-sized crystals but frequently the fluorite blocks were aggregates of millimetre-sized grains.

The breccia shown in Figs. 4 and 5 appears as cryolite fragments in a matrix of topaz. However, microscopy of a thin section showed that the main part of the matrix was a dense packing of irregular and wedge shaped cryolite grains ranging in size from a few hundred microns down to 5 – 10 µm. Only between these grains does topaz fill the interstices. This kind of breccia has

been observed as veins, centimetre-wide and up to 1 metre long, in metre-sized blocks of coarse grained cryolite bordering to brecciated cryolite with fluorite cemented by topaz. Similar vein breccias with fragments of cryolite and fluorite have also been found, and in drill cores from the fluorite zone centimetre-wide vein breccias with fluorite and some weberite, Fig. 6, were observed e.g. at the position marked vb on Fig. 1.

Topaz and cryolite

A remarkable appearance of topaz was observed in the lower parts of the west and north wall of the quarry: millimetre-thin veins of the mineral formed a wide-mesh net through coarse grained cryolite. Fig. 7 shows its appearance in an exploration drift in the foot of the north wall. The cryolite, here dark smoky, is fractured and the decimetre-big blocks are separated by the narrow topaz veins.

Horizontal drillings in the north and the west wall indicated around 10 m of this type of material: high-grade cryolite with 1 – 3% topaz. In several drillings a few metres of pure cryolite were encountered before the topaz-infiltrated cryolite, which was followed by a few metres of cryolite with some fluorite and topaz; fluorite-rich cryolite with topaz made up several metres up to the rocks of the surrounding intrusion.

Vertical drillings in the bottom of the quarry showed the cryolite-bearing parts of the deposit resting on cryolite-free, fluorite-topaz masses: the fluorite zone which showed thicknesses from 2 to 15 m averaging about 10 m (see Fig. 1).

Fig. 7. Part of wall in exploration tunnel 1.2 m by 0.8 m. Smoky cryolite transected by a three-dimensional network of millimetre-thin topaz veins. The uneven surface and the transparency of wet cryolite make it difficult to distinguish the thin topaz veins from local accumulations of topaz.
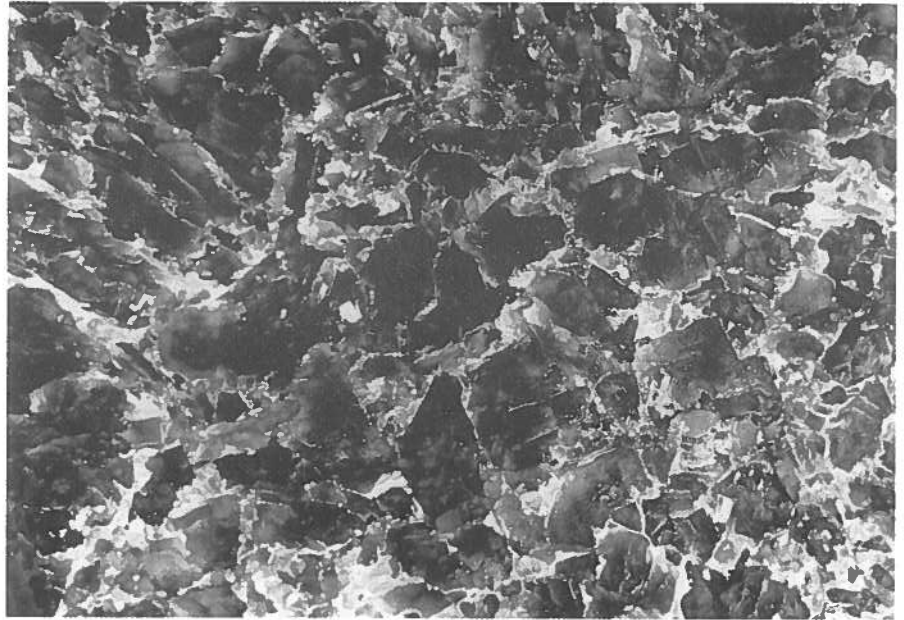
On broken blocks the high-grade cryolite transected by the topaz net exhibited large, plane or stepped surfaces covered by a thin layer of topaz. Surfaces 30 to 40 cm across have been observed, and stepped surfaces were more common. The single steps could be centimetre-wide but millimetre-wide, densely packed steps were frequently seen (Fig. 8). Several differently oriented stepped surfaces were often found on a single specimen. Fig. 9 shows an area where the steps appear as a cast of a number of close lying prismatic bodies. In thin sections the topaz veins show straight borders to cryolite.

Crystallography of topaz-covered planes in cryolite

In order to establish the crystallographic nature of the topaz covered planes, the plane angles, not the face-normal angles, have been measured with a contact goniometer, directly and on plaster casts and in thin sections cut at right angles to the edges of the steps.

In thin sections the topaz layers appear as zigzag lines (Fig. 10). The acute angles are close to 70°. Truncations show obtuse angles near 124°. The cryolite enclosed by the topaz lines show in some cases extinction between crossed polar which is symmetric relative to the line bisecting the angle. In other cases the extinction was inclined some forty degrees to that line. This is consistent with topaz covering planes from $\{011\}$ in the cryolite in the first cases and from $\{10\bar{1}\}$ and $\{101\}$ in the other cases.

Figure 11 shows a photograph and a drawing of a sample with several facetted steps where the following angles were determined: a = 109°, b = 70° and c = 126°. Repeated determinations on this sample and on a number of other samples gave values for "a" between 106° and 110°, for "b" between 69° and 73° and for "c" between 124° and 128°. Comparing these values with interfacial angles of cryolite it is seen that "a" and "b" are close to the angles between faces from $\{011\}$, $\{10\bar{1}\}$ and $\{101\}$ which are near 70° and 109°. These forms

Fig. 8. Topaz covered stepped surface, 7 cm by 5 cm, in coarse grained cryolite.
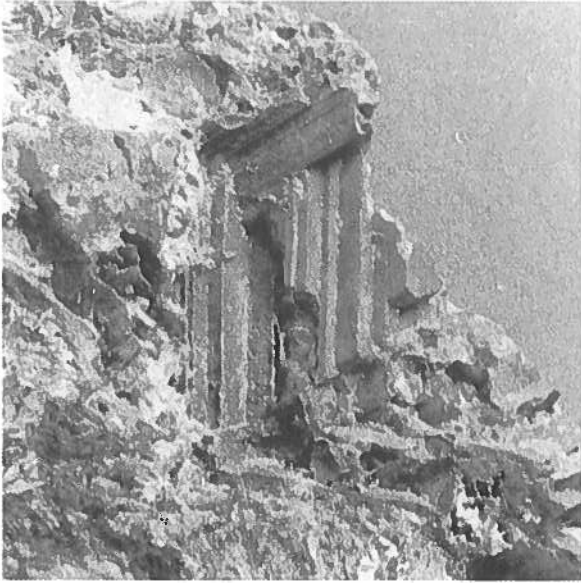
Fig. 9. Topaz appearing as two sets of parallel lying prismatic bodies 2–3 cm long. The cryolite, originally present within them, has been leached away and partly replaced by jarlite.

Fig. 11. Centimetre-wide steps in dense topaz where cryolite originally present has been broken away. The steps are 1 cm, 2 cm and 1 cm wide. The drawing shows the angles measured: a = 109°, b = 70° and c = 126°.

correspond to the cubic octahedron having angles of 70.6° between opposite faces and 109.4° between adjacent faces, because cryolite is pseudo-cubic (Donnay 1952) with a superlattice of multiplicity 2. As $\beta \approx 90°$ the transformation $1\bar{1}0/110/001$ produces a face-centred cubic array with $a_{cubic} \approx 7.76$ Å and a space-group symmetry of Fm3m (Hawthorne and Ferguson 1975).

In cryolite {110} and {001} correspond to the cube. Faces of the octahedron and of the cube form angles of 125.3° and 54.7°. The angle "c" (Fig. 11), found to be 126°, may therefore represent a face of the pseudo-cube cutting a face of the pseudo-octahedron.

In some cases prismatic bodies have been found showing angles close to 145°. As faces of the rhombic

Fig. 10. Two thin sections, plane light, picture 1.4 cm high. The sections are cut perpendicular to topaz filling fissures in cryolite. Quarts grains and crystals were seen in the interior of the broad topaz veins. The angles between the topaz covered surfaces in the cryolite are close to 70° and 124°.
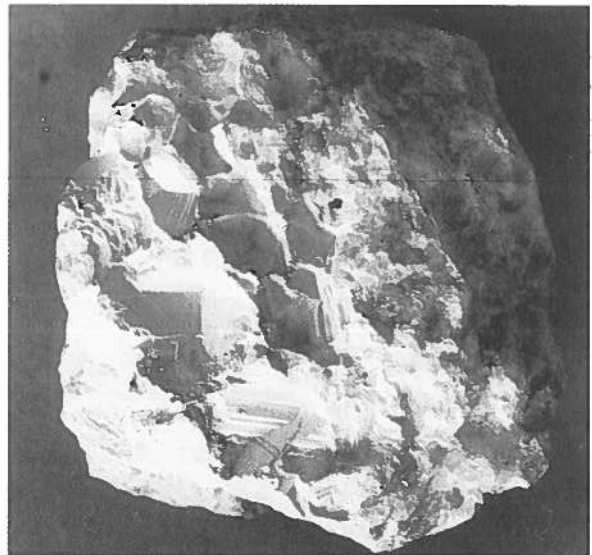
Fig. 12. Sample, 8 cm by 8 cm, of massive topaz with imprints of crystal-like shapes.

Fig. 13. Cast in topaz resembling a group of crystals, 3.3 cm high, in parallel growth showing faces corresponding to the pseudo-octahedron and the pseudo-cube of cryolite.
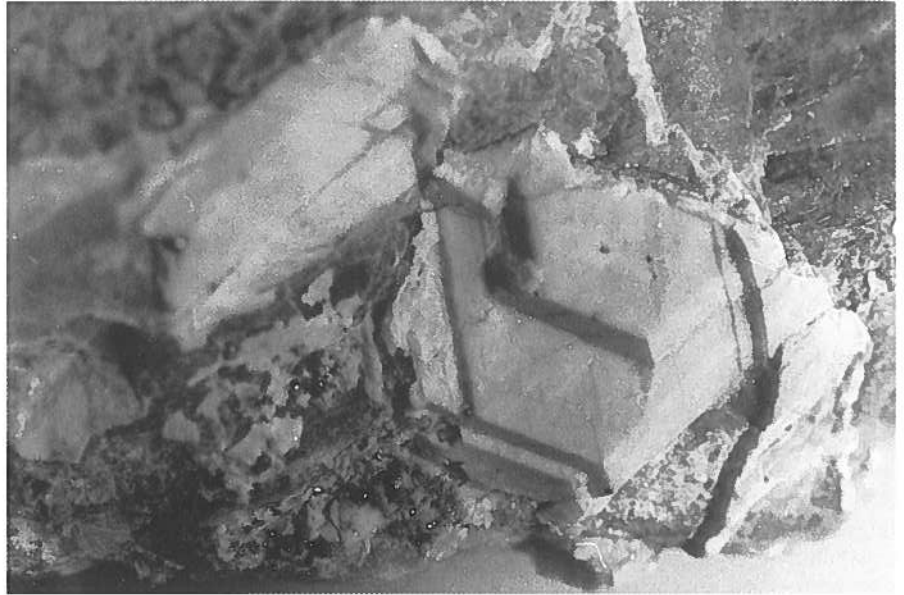
dodecahedron form angles of 144.7° (and 35.3°) with faces from the octahedron these prismatic bodies show faces of the forms in cryolite corresponding to the octahedron and the rhombic dodecahedron. In cryolite the forms corresponding to the latter are {100} and {010} besides {112} and {$\bar{1}$12}.

The stepped surfaces can be regarded as a number of parallel aligned prisms. A simple prism represents the four pseudo-octahedral faces in cryolite: {101} and {10$\bar{1}$} or those of {011}. Truncations of the obtuse angles by faces of the pseudo-dodecahedral form of cryolite {100} in the first case and of {010} in the second case result in prisms with interfacial angles of 70° and 145°. If the acute angles are truncated by the pseudo-cube faces of {001} it results in prisms with two angles of 110° and four of 125°.

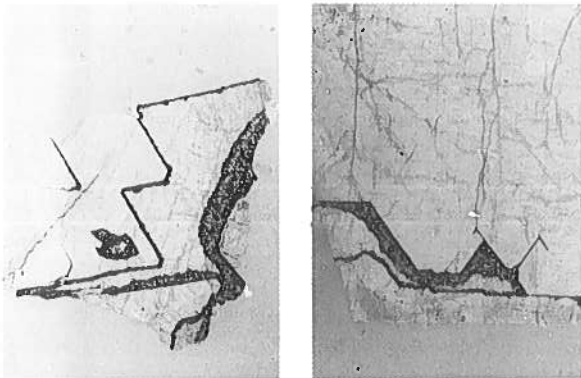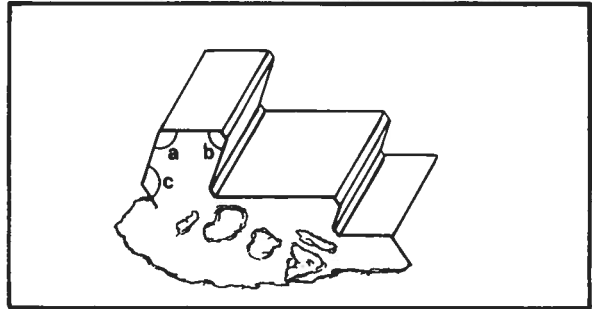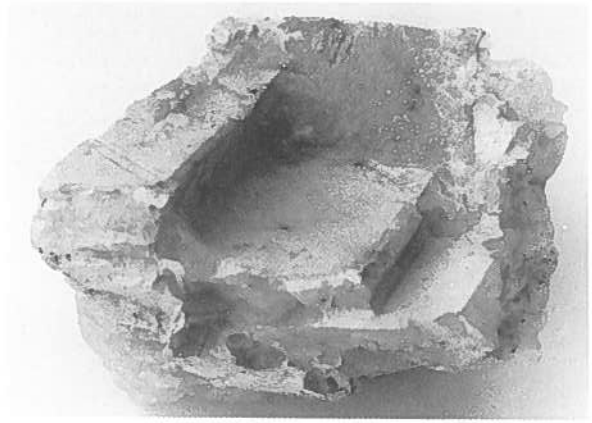In other words the topaz net in high-grade cryolite transects the cryolite along planes corresponding to the pseudo-octahedron, the pseudo-cube and the pseudo-dodecahedron. It was faces of the first two types which were found covered by topaz/"ivigtite" films in coarse grained cryolite mentioned by Pauly (1978).

Frequently samples containing massive topaz were found with crystal-like imprints, see Fig. 12. Cryolite fills these casts but it often falls out when the sample is broken. Such imprints can also be obtained by dissolving cryolite present in massive topaz. The angles measured on plaster casts of the imprints were the same as those found on the prismatic bodies from the stepped surfaces. A few samples with positive casts in topaz of crystal-like shapes have also been found. Fig. 13 shows such a cast which resembles a group of crystals in parallel growth showing faces corresponding to the pseudo-octahedron and the pseudo-cube. These crystal-like

casts may have formed where several systems of stepped surfaces happened to intersect (compare Fig. 8).

Cleavage in cryolite and topaz emplacement

The crystallography of the topaz-covered plane and stepped surfaces show that the coarse grained cryolite prior to the introduction of the topaz had been subject to mechanical forces creating fissures in the cryolite. These forces must have acted under particular conditions because they gave rise to planar fractures in the mineral following planes of the pseudo-octahedron {101}, {10$\bar{1}$} and {011}, one of the planes of the pseudo-cube {001} and planes of the pseudo-dodecahedron {100} and {010}.

Under normal conditions the mineral cryolite shows pronounced parting along {110}, that is planes of the pseudo-cube. This parting is clearly related to systems of twin lamellae following these planes (Bøggild 1912, Pauly 1978). Pauly (1978) found indications for a fair cleavage along (001) and a possible but weak cleavage along (101). Krenner (1883) reported cleavage along ($\bar{1}$01) but Bøggild (1912) found it hardly probable.

The topaz-covered plane faces along octahedral, cubic and dodecahedral planes mirror in their mutual frequencies the ranking of lattice planes in face-centred cubic crystals: (111), (001) and (110). It may beforehand be difficult to understand that the monoclinic mineral cryolite with its complicated pattern of twin lamellae systems can reproduce these features in the topaz-

decorated plane faces but it becomes clear when one realizes that all twin operations in the mineral correspond to the operations of symmetry in a cubic mineral (Bøggild 1912, Donnay 1952).

Exceptional conditions may lead to pronounced cleavage in the mineral quartz: under normal conditions cleavage is extremely weak but it is quite common in quartz from explosive and crypto-explosive structures (Carter 1968). By analogy to this, it is assumed that the shattering of cryolite resulting in plane fractures was due to explosion-like events which took place after the consolidation of the body of pure, white cryolite, see Fig. 1.

Descriptions of dykes with fluidized emplacement (Hogarth et al. 1988) apply equally well to the vein breccias (Fig. 4 and 6) containing centimetre-sized cryolite fragments embedded in a mass of densely packed, fine grained, irregular and wedge-shaped cryolite fragments with topaz filling the interstices. These vein breccias can also be regarded as products of a series of events: build-up of gas-pressure, rupture of the overlying consolidated parts of the deposit and rapid introduction of debris into the fissures in a stream of gas.

This picture of the formation of the vein breccias is in keeping with the assumption that explosion-like events caused cleavage fissures in the coarse grained cryolite subsequently filled by topaz even where the fissures were less than 50 μm wide, Fig. 10.

Vein breccias containing fluorite instead of cryolite indicate that the same type of events took place in fluorite-rich surroundings. Observations of such vein breccias even from the deeper parts of the fluorite zone show that these events were not confined to the overlying cryolite-carrying masses, Fig. 6.

Formation of topaz

The cryptocrystalline, flint-like character of the topaz and the invariable connection of topaz with breccias in the fluorite-cryolite as well as in the fluorite zone indicate that the formation of this mineral took place under the same conditions throughout these masses. The autobrecciation observed in the veins of topaz points to repeated pulses in their formation. This feature of repetition complicates the appearance of breccia structures involving the other minerals.

The monomineralic character of the white topaz of the vein shown in Fig. 2 is typical of the major part of topaz present in fluorite-cryolite as well as in the fluorite zone. Topaz with greenish colours is frequently found to contain small amounts of "ivigtite" and purple coloured topaz contains disseminated fluorite. Crystals of quartz, 50 μm or less in size, were observed within some of the topaz veins shown in Fig. 10.

No signs of corrosion or chemical reactions are observed between cryolite and topaz. This is clearly illustrated by the sharp-edged and wedge-shaped fragments of cryolite in the vein breccias (Fig. 5). In the fluorite zone where most of the topaz of the deposit was present cryolite occurred only along the border to the overlying fluorite-cryolite. Topaz obviously precipitated as such in the veins and in breccia matrices.

Topaz and chiolite

An exception to the above relations is the formation of topaz linked with brecciated chiolite transformed into cryolite along the rims of the fragments (Pauly 1986a). In thin sections the chiolite to cryolite transformation appears as a solid state replacement. The proposed reaction scheme in Pauly (1986a) assumes volume by volume replacement of chiolite by cryolite and is probably too simplified. Nevertheless, the formation of topaz in these surroundings is of some interest. The "topaz-cryolite" particularly observed in the chiolite milieu (Bøgvad 1938, Pauly 1986a) is chert-like in appearance and is a fine grained aggregate of cryolite containing 1 – 2% "topaz". It formed through transformation of chiolite alongside the veins of cryolite with the thin strings of topaz. Determination of the Li content of "topaz-cryolite" showed 5 ppm Li (Pauly 1986b) in good accordance with 8 ppm Li in chiolite whereas all other types of cryolite average 92 ppm. Microprobe analyses showed that the "topaz-cryolite" contained both topaz and tiny crystals of a well crystallized K-mica, roughly in equal amounts. This is of interest because microprobe analyses of chiolite have shown this mineral to contain 0.3% K. The transformation of chiolite to cryolite thus liberated both Al and K which reacted with the silica added to the system in connection with the breakdown of the chiolite and thereby formed topaz and K-mica.

The formation of topaz and of K-mica through breakdown of chiolite raises the question whether all topaz (about 150000 tons) and all "ivigtite" (about 50000 tons of this spherulitic K-mica) in the deposit formed this way. Calculations show that it would presuppose unacceptably large amounts of solid chiolite (about one million tons) before the reactions took place. Apart from this the parallel formation of cryolite would vastly exceed the amounts found in fluorite-cryolite. To this can be added that the Li concentrations in cryolite from fluorite-cryolite were at the same level as in cryolite from the other major cryolite types (Pauly 1986b).

Topaz and fluorite

The conditions under which topaz formed prevailed throughout the masses of the fluorite-cryolite and the fluorite zone but in fluorite-rich parts, particularly in the fluorite zone, the structural pattern established in

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Fig. 14. Section through drill core, 3.2 cm wide, from the fluorite zone. Colloform fluorite repeatedly festooned by topaz.
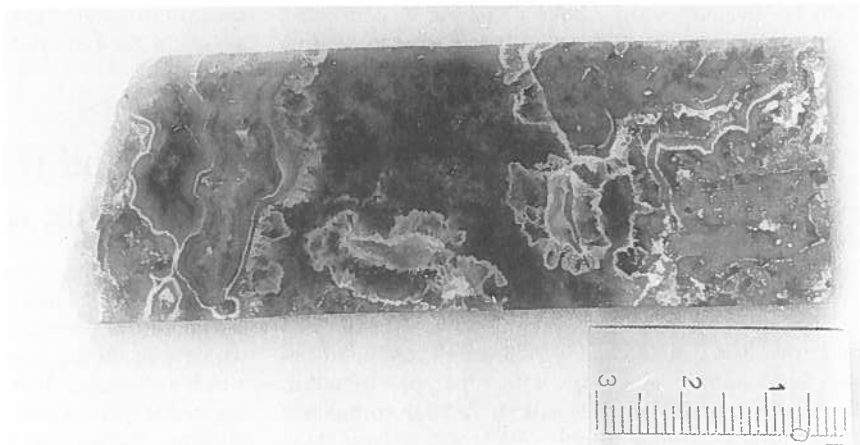
the material by the topaz deviates in some respects from that hitherto described. The reason for this is that fluorite not only consolidated before topaz giving rise to fragments of fluorite cemented by topaz, but fluorite also consolidated contemporaneously with topaz and it continued crystallizing after precipitation of topaz ceased (Fig. 14).

The major part of the fluorite shows agate-like concentric zoning, in appearance it is colloform. It may be found in millimetre– to centimetre-sized, rounded masses exhibiting botryoidal shapes. In thin sections it is seen that the zoning arises from varying densities of pigments and micron-sized holes. This pigmentation can also be seen to mark radiating lines. Thin layers of topaz can be seen between the zones and some zones may contain scattered topaz crystals 20 – 30 µm long. Moreover, on cut and polished samples, festoons of topaz can be seen on broken-up pieces of the botryoidal fluorite (Fig. 14). Late fluorite fills up the concave space be-

tween these fragments; in this fluorite there are occasionally seen small cavities a few millimetres but sometimes up to a few centimetres across. The fluorite may form crystals protruding into the cavities. The late fluorite appears rather clear in thin sections because it contains only little pigment.

Topaz-rich masses from this fluorite-rich milieu may appear as centimetre-sized rounded nodules of slightly coloured topaz embedded in colourless topaz (Fig. 15). The nodules appear on cut and polished sections as partly zoned encrustations containing elongated aggregates of fluorite grains. These aggregates may also form zones within the nodules. Accumulations of very small fluorite grains in the topaz often form a slightly coloured outer zone to the nodules. The interstitial, colourless topaz seen on a polished surface with a lens looks as if it were composed of sand-grains 1/4 to 1/2 mm across. An opaque, white mass is seen between the densely packed grains. The grains, observed in plane

Fig. 15. Sections through topaz-rich drill cores, 3.2 cm wide, from the fluorite zone, right, and from fluorite-cryolite, left. Right: rounded nodules of topaz with inclusions of fluorite in a matrix of white topaz. Left: compact topaz showing sediment-like structure with inclusions of rounded fragments of topaz crusts (not showing up in the picture), fragments of cryolite and fluorite appearing dark in the picture. Vesicle-like inclusions are filled by aggregates of well-crystallized K-mica.
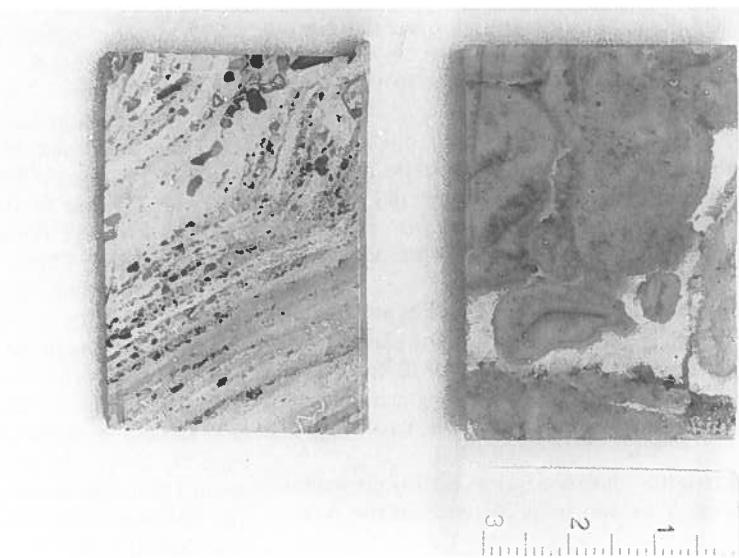
light in the microscope, have pigments in concentric zones. Between crossed polars they appear as fine grained flint-like aggregates. The opaque, white mass between the grains is fibrous topaz much coarser than the topaz in the grains: between crossed polars with gypsum plate it appears as a rectangular grid of blue and yellow ribbons confining the grains. The colourless topaz between the nodules obviously has a rather high degree of ordering of its fibres, though it may also form spherules up to 1/4 mm across. Irregular, colourless, rounded grains of fluorite are present in this topaz.

The topaz-rich masses frequently show sediment-like and crust-like structures (Fig. 15). In all cases consolidation of fluorite alternates with topaz precipitation. Repeated episodes of brecciations further complicate the picture, individual samples may show at least three periods of brecciation.

Topaz, fluorite and late minerals in the fluorite zone

In the samples from the fluorite zone fluorite and topaz dominate. They make up more than 80% of the total mass. The remaining constituents are weberite (5 – 6%), "ivigtite" (7 – 8%) and jarlite (0.4%). Together with the latter small amounts of stenonite have been observed in several drill cores (Pauly 1962). Celestite and more frequently strontian barite may be present along with jarlite and ralstonite has been seen in some cases. Besides these minerals, prosopite crystals have been found on crystals of the late fluorite in the cavities into which this fluorite protrudes.

The late fluorite furnishes a clear basis for setting up the paragenetic positions of the various minerals. Prosopite obviously formed after this fluorite. Jarlite and its accompanying minerals were found within this fluorite. Jarlite and ralstonite might form crystals protruding into the cavities but grains of jarlite can also be seen dispersed in the fluorite. It formed after but also contemporaneously with the late fluorite.

Weberite is found as dendrites growing out from the colloform fluorite. The dendrites of weberite pass into areas of granular weberite away from the contact against the fluorite. Fragments of weberite and colloform fluorite were found in vein breccia with topaz (Fig. 6).

Weberite may also occur as isolated grains and aggregates within the clear, late fluorite. In some samples, it, so to say, took the place of the late fluorite but it also formed together with this fluorite. In larger masses of weberite "ivigtite" may occur as isolated, small aggregates.

Otherwise "ivigtite" forms concave inclusions within the late fluorite. This and its occurrence in the inter-stices in brecciated masses of the other minerals place it as one of the last minerals to form in the fluorite zone.

Topaz and the development of the cryolite deposit

Formation of the fluorite zone started with crystallisation of fluorite. Then came the main mass consisting of the colloform fluorite which consolidated in alternation with topaz during a period with repeated brecciations which are marked by topaz. Weberite started crystallizing in this period and continued together with the late fluorite. Jarlite and the minerals associated with it formed after the late fluorite in irregularly disseminated pockets here and there in the mass though some jarlite also crystallized within the late fluorite. "Ivigtite" formed after the late fluorite.

In the fluorite-cryolite the minerals observed in the samples from the fluorite zone are also present and they mutually show the same sequence of formation. They are all later than cryolite and either replace this mineral or are present in fractures in this mineral. Weberite and jarlite formed larger accumulations in the fluorite-cryolite than in the fluorite zone. Calculations given below (Table 1) show that the proportions of weberite, jarlite and also "ivigtite" relative to fluorite increased about two times in the fluorite-cryolite compared to the fluorite zone.

The uniform formation of topaz right through the masses of the fluorite-cryolite and the fluorite zone establishes a common feature which can be used in the interpretation of the development of the deposit after the consolidation of the siderite-cryolite and the body of the pure, white cryolite formed in what can be called Stage 1. The fluorite-carrying masses formed in the following stage, here called Stage 2.

The mode of occurrence of the topaz shows that the transition from Stage 1 to Stage 2 came about through violent explosions. The cryptocrystalline topaz penetrated into cleavage fissures in coarse grained cryolite; it filled the interspace in vein breccias containing fragments of cryolite or fluorite embedded in fine grained debris of cryolite or fluorite; it formed the matrix in breccias of coarse grained cryolite and/or fluorite and vein-like fissure-fillings of topaz were formed through repeated injections which broke up earlier deposited topaz followed by renewed topaz precipitations.

A profile through the deposit along a centrally placed E-W line shows the locations of the products of Stage 1 and Stage 2 (Fig. 1). The topaz-veined cryolite has been indicated in a schematic way based on observations from the lower 3 to 10 m of the walls over a distance of about 120 m (the western and part of the northern wall). The position of the decimetre wide and more than 50 m long vein of topaz, observed in the foot of the west wall

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in 1937, is marked on the profile. Here is also indicated the position of the "jarlite-druse" some 20 m above the topaz vein. According to the unpublished report by R. Bøgvad it was also observed in 1937. It consisted of decimetre thick segregations with jarlite stretching continuously about 7 m north and south of the section shown in Fig. 1.

The violent explosions connected with the *mise-en-place* of the topaz were accompanied by caving-in of large masses of the cryolite which formed the roof of a cavity containing the still unconsolidated residue left over from the processes in Stage 1. The coherent cryolite above the cavity became highly fissured. Fluids depositing the cryptocrystalline topaz pervaded these fissures. The fragmented cryolite mingled with the residue in which fluorite started consolidating as colloform and botryoidal masses presumably due to the sudden drop in pressure and temperature. Previously consolidated fluorite was shattered and transected by topaz as was the solid cryolite. Repeated violent events broke up the topaz-coated botryoidal fluorite masses; continued growth of fluorite and renewed topaz precipitation gave these brecciated masses an appearance quite different from ordinary breccias.

The cryolite fragments stayed in the upper parts of the unconsolidated residual material and gave rise to the fluorite-cryolite. Within the fluorite-cryolite, there is a downwards decrease in the content of cryolite. At lower levels, the formation of the fluorite zone – cryolite-free fluorite-topaz masses – took place.

Calculations indicate that the products of Stage 2 comprised 24% and the products of Stage 1 amounted to 76% of the total volume of the fluorite zone, the fluorite-cryolite and the siderite-cryolite. The above suggested development of Stage 2 has as a consequence that all cryolite in the fluorite-cryolite originally be-

longed to Stage 1. By addition of this cryolite its volume then rises to 86%. Thomsenolite and associated minerals formed by decomposition of 2% cryolite in Stage 3. The residue left from the processes in Stage 1 corresponds in solid matter to a volume of 15% that is close to 200000 m^3 which swept around the lower western part of the consolidated masses formed in Stage 1. The original volume must have been larger but hardly twice the calculated volume because collapse of such a volume would be connected with displacements of the surrounding solid masses amounting to several scores of metres. Observed displacements in brecciated areas in the quarry amount to less than 10 m.

Composition of residue after Stage 1

The residue in the cavity, left over from Stage 1, had a composition which allowed the formation of the fluorite zone and, mingling with the shattered cryolite, it also gave rise to the fluorite-cryolite as visualized in Fig. 1.

Mineralogical analyses of drill cores from the fluorite zone and fluorite-cryolite supplemented with analyses of 74 cargoes of crude fluorite-cryolite representing 96000 tons have been used as a basis for calculating the compositions of these masses (Table 1). The analyses of the crudes were mineralogical analyses combined with chemical determinations of Ca, Mg, SiO_2 and Na, the latter being representative of cryolite, chiolite, weberite and thomsenolite.

In the calculations for Table 1 the contents of quartz. siderite, sulphides and thomsenolite have been omitted because these minerals entered the fluorite-carrying

Table 1: Contents of the five major minerals of the fluorite zone, recalculated to 100%, in the fluorite zone, the fluorite-cryolite and in four sub-samples of fluorite-cryolite.

	Fluorite zone drill core analyses	Fluorite-cryolite	Fluorite-cryolite sub-samples			
			Drill core analyses 290000 tons	74 cargoes crude cryolite 96000 tons[*]	West wall exposure 2 tons	North wall exposure 32 tons[*]
Fluorite	56.3%	55.1%	55.0%	54.3%	60.7%	43.7%
Weberite	5.7%	10.1%	3.7%	20.4%	2.3%	25.1%
Jarlite	0.4%	0.9%	1.1%	1.0%	1.6%	4.1%
Topaz	29.9%	20.6%	24.3%	13.6%	10.9%	20.5%
K-mica	7.7%	13.3%	15.9%	10.7%	24.5%	6.6%
Original sum	93.5%	20.3%	27.1%	10.3%	44.0%	60.9%
Cryolite	–	72.7%	67.6%	81.1%	51.7%	29.7%

[*] The mineralogical analyses were here combined with chemical analyses.
Note: The diamond drill cores represent vertical drillings in the bottom of the quarry, downward inclined and horizontal drillings in the foot of the walls (Fig. 1). In 1951 the west and the north wall samples were collected in exposures of fluorite-cryolite in order to supplement the drillings. The analysis of fluorite-cryolite was established by combining the drill core analyses with the analyses of the cargoes of crude cryolite shipped between 1957 and 1963 because they came from quarrying in the walls.

masses due to brecciations in border zones and due to quarrying in border zones; thomsenolite formed after fluorite-cryolite through decomposition of cryolite in the final stage of the development of the deposit (Stage 3). Concerning quartz it should be mentioned that small amounts originated in the Stage 2 processes but they are too small to show up in these calculations.

It is seen (Table 1) that the content of the tabulated minerals in fluorite-cryolite is not merely the result of addition and dilution by cryolite. The proportions of the Mg, Sr-Ba- and K-bearing minerals relative to fluorite (weberite, jarlite and "ivigtite") are higher in the fluorite-cryolite than in the mass of the fluorite zone. The calculations given in Table 1 underline this and the four sub-samples of fluorite-cryolite also illustrate large mutual variations among the five minerals: no coupling is indicated between these minerals or pairs of minerals.

Late minerals from Stage 2 in fluorite-cryolite

When the residue left from Stage 1 started consolidating, colloform fluorite precipitated leaving fluid phases giving rise to local accumulations of the late minerals weberite, jarlite and " ivigtite" in highly varying proportions. Independently veins of pure topaz transected the consolidating masses and formed the matrix for fragments of the earlier consolidated masses. The mobile phases and the fluid phases were partly retained within the fluorite zone but part of them escaped from the fluorite zone and gave rise to a considerable amount of weberite, jarlite and "ivigtite" in fluorite-cryolite. Slightly more than 1/3 of the total amount of these minerals found in the deposit occurred in the fluorite-cryolite. In addition, 1/4 of the fluorite and 1/5 of the topaz was located in fluorite-cryolite.

Weberite

Weberite can form rather pure, compact masses in the fluorite-cryolite. Cavities are rare and small in these samples. Dense masses of weberite also form vein-like fillings between cryolite fragments. Dendrites, and tendencies to dendritic development of the weberite are frequently observed in thin sections. Weberite sometimes seems to have replaced the cryolite from shattered siderite-cryolite. Siderite is clearly fractured; larger aggregates of sphalerite may also show fractures and quartz crystals may be transformed to albite or topaz in these samples. Weberite often contains "ivigtite" as small clusters and, although veins of "ivigtite" through weberite are present in many samples, they are not necessarily connected with the small clusters of "ivigtite".

Some of the weberite found together with jarlite is peculiar because it is often mantled by ralstonite which forms crystals lining cavities in these samples.

Jarlite and associated minerals

Jarlite in the fluorite-cryolite occurred in fluorite-rich masses in the same manner as in the fluorite zone. It is, however, of particular interest that jarlite made up the major part of large aggregates forming metre long, decimetre wide fissure-fillings. These aggregates have a peculiar structure which caused Bøgvad (1933) to name them columnar aggregates. Besides jarlite (50% or more) they carry fluorite, topaz and "ivigtite", some barite and other minerals. Many samples may be termed radiating aggregates. Bøgvadite (preceding jarlite) was first observed in such aggregates (Pauly & Petersen 1988).

These jarlite-bearing aggregates were characteristically rich in cavities lined by crystals of jarlite as well as thomsenolite and ralstonite (Bøgvad 1933, Pauly & Petersen 1988). They owe their peculiar structure to the arrangement of the fine grained topaz and "ivigtite" preceding the formation of the Sr-Ba-minerals. A detailed account is in preparation.

Dendritic jarlite was originally assumed to be a mineral distinct from jarlite by Bøgvad (1933) who called it "meta-jarlite". It was found together with brecciated chiolite. Bøgvad (1951) reported "rather large veins" of it from a location in the quarry far removed from the occurrences of chiolite. The veins, or rather fissure-fillings, some centimetre wide and about one metre long, transected siderite-cryolite bordering onto fluorite-cryolite. They consisted of dense, monomineralic masses of dendritic jarlite. Cavities were sparse and small.

From the same location a few years later came the samples containing stenonite (Pauly 1962). Weberite and fluorite together with jarlite were present with the stenonite as the major minerals in the paragenesis. Weberite and fluorite formed earlier than the Sr-minerals and it seems that thomsenolite and ralstonite formed later in reactions with surrounding cryolite (Pauly 1962).

Some samples of the vein-like, dendritic jarlite show the jarlite bordering onto fine grained masses of weberite, the dendrites growing out from the contact between the two minerals. Grains of stenonite, 50 µm and less, have been found in a few of these samples.

It should be noted that the jarlite found together with stenonite is perfectly well crystallised in contrast to the dendritic jarlite and jarlite from the columnar and radiating aggregates which always show undulating or brush-like extinction between crossed polars.

"Ivigtite"

"Ivigtite", a local name for a green spherulitic K-mica (phengitic), formed irregular veins and fissure-fillings in the fluorite-cryolite. It appeared in the same way in siderite-cryolite and in pure cryolite bordering to fluorite-cryolite. Pure, dense masses of this mica have also been found as the matrix for brecciated cryolite where fluorite, weberite and jarlite could also be present enclosed within or veined by it. Together with topaz, it has been found decorating cleavage fissures in cryolite. Microscopy of thin sections shows that topaz formed before the mica. This combination of topaz and "ivigtite" is present in the jarlite-carrying columnar and radiating aggregates. In the central parts of the latter, where bøgvadite was discovered, tangential bands of "ivigtite" accentuate the radiating structure (Pauly and Petersen 1988).

Together with the spherulitic "ivigtite", grains of well crystallized mica have been observed in a number of different samples. Besides greenish patches of "ivigtite" some weberite samples also contain bluish patches in which tiny flakes (about 200 µm across) of mica can be seen. In thin sections this mica can also be found as parts of "ivigtite" aggregates. A few samples of weberite and colloform fluorite with fragments of cryolite contain a few per cent of a vivid yellow mica forming flakes up to 1 mm across. A similar mica has been observed with stenonite and stenonite found in a drill core from the fluorite zone occurs together with centimetre-sized flakes of purple and also colourless mica (Pauly 1962). These last two micas give X-ray diffractograms resembling muscovite. Microprobe analyses indicate that these well crystallized micas are K-micas with compositions similar to that of "ivigtite". Chemical analyses of "ivigtite" and of a sample of blue-green mica both revealed K-micas with a few per cent of Fe, a little Mg and Si:Al greater than 3:1 . The content of Li was about 300 ppm in "ivigtite" and 60 ppm in well crystallized mica (Pauly 1986b).

These well crystallized K-micas are probably expressions of locally improved conditions for the formation of the K-silicate within the deposit. In general it formed spherulitic masses.

Character of mineralizing masses/fluids

The residue left over from Stage 1 can be regarded as a mass from which mineralizations arose. The appearances of the products of the mineralizations and their locations reflect the properties and conditions of these mineralizations.

Fluorite developed mainly as colloform masses forming up to centimetre-sized botryoidal bodies. Later fluorite crystallized enclosing cavities into which crystals of fluorite protruded.

Topaz, pure, formed cryptocrystalline fillings: in fissures, from 50 micron to decimetre wide, and between fragments of topaz, cryolite, fluorite and weberite.

Weberite grew on colloform fluorite as dendrites passing into granular masses. Irregular masses of weberite, granular but with dendritically developed patches, were found replacing brecciated siderite-cryolite. Rare, small cavities lined by crystals of weberite were observed in these masses.

Jarlite in pure, dendritic masses formed fissure-fillings in siderite-cryolite. The major part of jarlite was found in the radiating and columnar aggregates filling decimetre-wide fissures in fluorite-cryolite. The aggregates also contain topaz, "ivigtite" and fluorite. Jarlite occurs as fan-shaped grains showing brush-like extinction between crossed polars relating them to spherulitic forms; they may be termed sub-spherulitic. True spherules of jarlite have also been observed. Jarlite with some bøgvadite and barite replaced cryolite. The radiating aggregates are rich in cavities lined by crystals of jarlite, thomsenolite and ralstonite. The decimetre-sized radiating aggregates with bøgvadite appear as large colloform aggregates.

"Ivigtite" occurred as pure, fine grained, spherulitic masses filling fissures and forming the matrix for breccias of cryolite, fluorite and other minerals.

The colloform fluorite, the cryptocrystalline topaz, the dendritic weberite and jarlite and the spherulitic "ivigtite" with the first two representing more than 80% of the residue indicate unusual conditions and very rapid consolidation.

The formation of fissure-fillings of pure topaz indicates fractionation of this material from the residue. The extraordinary penetrativeness of the mass depositing topaz points to a gaseous medium. The amounts of topaz show that this fraction represented 1/4 of the residue. It obviously only carried Al, F, Si and O in nearly stoichiometric proportions as the only other phase (quartz) has only been observed in tiny crystals in a few cases within thin topaz veins (Fig. 10).

Fractions capable of depositing weberite arose after the consolidation of the colloform fluorite, i.e. after nearly 90% of the fluorite zone had crystallized. Weberite made up 6.9% of the products of the residue, and two thirds of this remained in the fluorite zone. Whereas the weberite in the fluorite-cryolite sometimes seems to have replaced cryolite this possibility was not obviously present in the fluorite zone. The Mg-rich mass giving rise to the weberite in this zone may have carried some Na and Al besides Mg. The rarity of cavities in weberite and the absence of other minerals such as ralstonite is interesting because it seems to indicate that water was not a significant component of the mass from which weberite formed.

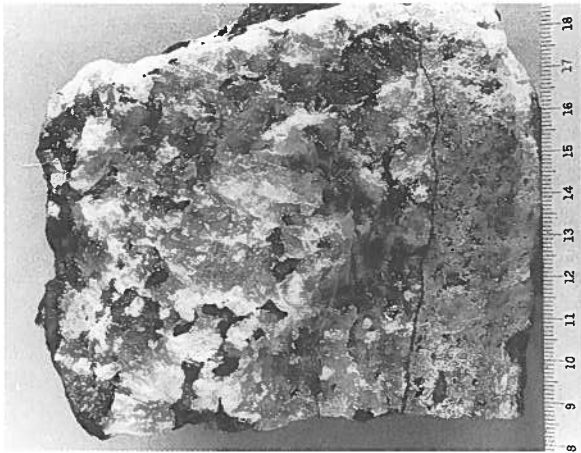The late fluorite though quantitatively of minor im-

Fig. 16. Sample of siderite-cryolite cut by a 2.5 cm wide vein breccia with prosopite. Scale in centimetre.

portance is interesting because of the cavities it contains; they indicate the presence of fluids or solutions. Prosopite crystals on crystal faces of the fluorite protruding into the cavities show that these late fluids carried Al besides Ca.

Fluids rich in Sr-Ba accumulated here and there in the fluorite zone giving rise to the small pockets of jarlite and associated minerals in which cavities with crystals of jarlite, ralstonite and other phases are indicative of the operation of solutions in the formation of these products which represent less than 1/2% of the products of the total residue. In the fluorite-cryolite, where about

1/3 of the jarlite from the residue was precipitated the picture is more complicated. A small fraction of the fluids depositing jarlite here gave rise to the mono-minerallic, dense fissure-fillings of dendritic jarlite in siderite-cryolite bordering the fluorite-cryolite. Addition of CO_2 in this milieu caused stenonite to form accompanied by well crystallized, coarse grained jarlite. Cavities with jarlite crystals and cavities with thomsenolite and ralstonite indicate the participation of water solutions in this mineralization.

The cavity-rich columnar and radiating aggregates with jarlite indicate accumulations in fissures of more complicated fluids and watery solutions active after deposition of topaz/"ivigtite" on cryolite. They caused dissolution of cryolite, concomitant crystallisation of bøgvadite and strontian barite followed by jarlite. The sub-spherulitic jarlite and the colloform development of the central parts of the radiating aggregates indicate consolidation from highly concentrated solutions or gel-like masses. The crystal lined cavities point to final activities of water solutions.

"Ivigtite" made up 10% of the products of the residue and about 1/3 was placed in the fluorite-cryolite. It formed from K-rich masses from which no other minerals precipitated; cavities are not present. In its occurrence it resembles to some degree topaz but it is clearly a late formation derived from the residue.
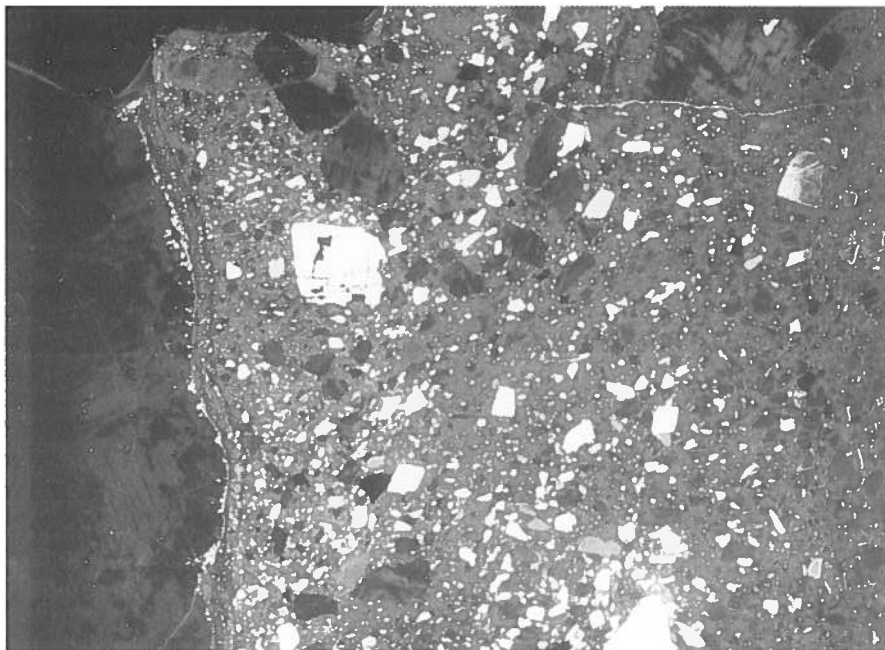
Fig. 17. Thin section, crossed polars, 2.5 cm by 1.9 cm. The section is cut from the vein breccia with prosopit shown in Fig. 16. To the left is seen the border of the vein to cryolite. Rounded but also sharp edged grains of cryolite are present in the vein together with fragments of siderite, quartz and sulphides. Prosopite is only present between the fine grained fragments. The micron-sized aggregates of prosopite can only be seen at high magnification and with difficulty because of the great differences in refractive indices between cryolite and prosopite; opaque microscopy solved this difficulty.

Fig. 18. Prosopite-cryolite appearing as a fine grained "sediment". The darker layers are rich in cryolite, the lighter are prosopite-rich. The dark area to the left is cryolite. The sample is cut and polished; scale in centimetre.

Stage 3, the closing stage of the cryolite deposit

The activity of the residue did not cease with the consolidation of the fluorite-cryolite. Prosopite and thomsenolite, ralstonite, gearksutite and other phases formed in fissures and solution cavities in all types of cryolite within the deposit.

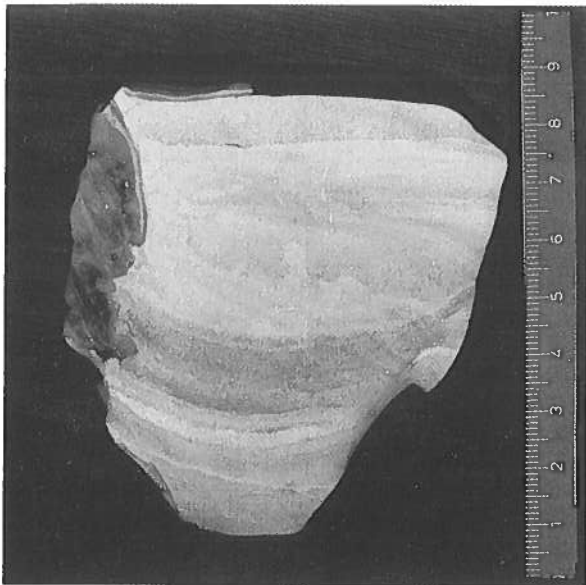Besides the main elements (Ca, Al, Na, Mg) some Sr has been found: 0.3% – 1.5% in prosopite (microprobe analyses), 0.5% and 1.6% in thomsenolite and pachnolite (wet-chemical analyses, Pauly 1982), 0.3% in gearksutite (atomic absorption spectrophotometry). The presence of Sr is interesting because it appears to link the solutions from which these minerals were formed with those responsible for the formation of the late minerals in Stage 2.

Prosopite

Prosopite has been observed in vertical veins or fissures in the walls of the quarry (R. Bøgvad 1937, unpublished report). The fissures were from paper-thin up to several centimetre wide. They cut through all types of cryolite from the foot of the walls to the border of the cryolite mass against the surrounding rocks, *i.e.* over some thirty metre (Fig. 1). They occurred in the west wall with a spacing of not more than 3 m. It should be noted

that they were not seen before 1937 nor were they found after 1954; they were obviously confined to a zone in the outer parts of the cryolite mass (Fig. 1).

The prosopite veins often contained thomsenolite and associated minerals in the central part or along the one side. Samples of the veins, usually show only one half because they easily split along the part with thomsenolite. Fig. 16 shows a thin section of a centimetre wide vein cutting siderite-cryolite. The material constituting the vein is a mixture of fragments of the minerals found in this type of cryolite: cryolite, siderite, quartz and sulphides. They range in sizes from millimetres down to 5 – 10 μm. Prosopite is only present as aggregates of micron sized crystals between the densely packed fragments of the other minerals. The larger cryolite grains are rounded, the smaller grains may be sharp-edged (Fig. 17). Reaction rims or corrosion are not observed either on these grains or on the cryolite bordering the vein. Thin veins of thomsenolite cut across the vein material and pass into the surrounding siderite-cryolite. A selvage of thomsenolite, 20–30 μm wide, follows the border of the vein to the surrounding siderite-cryolite. The cryolite/prosopite of the vein is very fine grained in a 1 mm wide zone along the selvage.

The peculiar character of these prosopite veins is clearly a parallel to the cryolite/topaz vein breccias (Fig. 5).

The cryolite/prosopite vein breccias indicate fluidized emplacement of debris in the vertical fissures: escape of pressurized gases forced fragmented grains up into the fissures and prosopite precipitated between these grains. Similar vein breccias, one millimetre or less in width, have been observed in samples of chiolite and in jarlite bearing samples. The formation of thomsenolite took place after the settling of the breccia-vein.

Another type of prosopite-carrying material is shown in Fig. 18. These samples resemble very fine grained sediments and are yellowish in colour. They consist of cryolite grains, 20 – 50 μm, or rarely 100 μm across. Aggregates of micron-sized prosopite crystals form an intergranular. The lighter layers seen in the samples are prosopite-rich, the darker are cryolite-rich. X-ray powder diffractogrammes suggest ratios of cryolite to prosopite around 50:50 in the former and 80:20 in the latter.

In thin sections from the sample shown in Fig. 18 cryolite-rich layers were found to contain cryolite grains bounded by crystal faces. Small tapering areas of cryolite were only composed of densely packed polygonal grains of cryolite. Such grains show simple twins or appear untwinned whereas fragments of cryolite show polysynthetic twinning. These phenomena indicate that recrystallisation has taken place. Crosscutting thomsenolite areas and areas rich in ralstonite are found bordering against the prosopite-cryolite mass.

The conditions under which these masses formed were obviously very different from those giving rise to the cryolite/prosopite vein breccias. Whereas the latter

Fig. 19. Prosopite with a cavity, 4 cm by 3 cm, transected by closely spaced lamellae of prosopite.

formed through violent bursts the former appear to be the result of a rather quiet settling of fine debris possibly in fluid-filled fissures where even some sort of slumping seems to have taken place (Fig. 18).

The recrystallisation of the cryolite implies solution and redeposition. The fluids involved can not have had Ca ions in solution as this would give rise to formation of thomsenolite or pachnolite, (Pauly and Petersen 1983). Ralstonite would be expected if Mg ions were present. As mentioned these minerals occur in these prosopite-carrying sample but formed later than the consolidation of the prosopite/cryolite masses.

Thomsenolite in cavernous masses with prosopite

Light blue, dense masses of prosopite in highly cavernous blocks were revealed through blasting in the bottom of the quarry in fluorite-cryolite just above the fluorite zone (some 30 m south of position P on the section Fig. 1). Thomsenolite made up a major part; it was often present as water-clear crystals, several centimetres long, in the cavities but mostly occurred as compact aggregates of millimetre-sized crystals. Cavities in the dense prosopite showed rounded spherical and stalk-like shapes which glitter because of the tiny crystals on their surfaces. The spherical bodies, around 2 mm in diameter, show a radiating structure when broken. The stalks, 3 – 4 mm wide and centimetre long, show a radiating structure in their outer parts. In thin sections the dense prosopite viewed between crossed polars appears as a flint-like aggregate of grains around 20 μm across, sometimes spherulitic. Towards the cavities seen in the thin sections, the grains of the aggre-

gates grow larger and form crystals 100–200 μm long protruding into the cavities.

In cavities in prosopite, tabular crystals of jarlite around 0.5 mm and aggregates of such crystals can often be seen clinging to the rounded prosopite aggregates. In some cavities crystals of pachnolite, 1/2 cm long, can be found protruding from prosopite globules or forming stellate groups.

Besides thomsenolite, ralstonite makes up a considerable part of the material outside the prosopite. Ralstonite usually forms crystals with distinct sector-zoned internal structure, but here they are often mottled. Colloform fluorite, with a zonal arrangement of the pigments is present. Thomsenolite veins cut through the fluorite. The ralstonite is later than the thomsenolite and prosopite forms veins and lobes in both.

Some remarkable cavities in these samples can be observed within the prosopite masses. They may be 1 by 2 cm wide and long but 3 by 6 cm have also been observed. They are crossed by a densely spaced array of millimetre thick curved lamellae, see Fig. 19. Prosopite makes up these lamellae and some ralstonite may also be present. In one case ralstonite crystals dominated the material of the lamellae, which appeared in thin section as "rock candy". Here prosopite forms incomplete fillings between the lamellae, in other words between the crystals of ralstonite. The ralstonite of the lamellae forms crystals around 0.5 mm across on both sides of the lamellae. In the central part they carry a strong pigmentation of small crystals, 10 by 30 μm, optically identified as topaz. Thomsenolite also occurs as inclusions in the central part. The outer parts with crystal-shapes are free of inclusions and it is of particular interest to note that prosopite has not been found within ralstonite as inclusions.

Samples carrying cryolite show thomsenolite replacing this mineral along its parting directions as is well known from the common samples of thomsenolite and associated minerals from this locality (Bøggild 1953).

Apart from inclusions of earlier formed minerals from fluorite-cryolite and siderite-cryolite these prosopite-carrying samples contain the following minerals: thomsenolite, pachnolite, ralstonite, jarlite, topaz, quartz poikilitically including thomsenolite and ralstonite, and gearksutite as white earthy masses in some cavities. Similar looking white masses were found to be a kaolin-like mineral containing minute fluorite crystals. White powdery barite was observed in a fissure in prosopite. Wulfenite crystals on thomsenolite and ralstonite have been observed in some samples (Leonardsen et al. 1981). Adjacent cavities in these samples can often be found to contain totally different mineral assemblages. Crust-shaped or stalactitic fluorite (Bøggild 1953) is also found with the prosopite and is treated separately below.

In spite of the paragenetically complicated relations, it is clear that cryolite being replaced by thomsenolite represents an earlier activity and that prosopite entered

Fig. 20. Cavity with thomsenolite crystals surrounded by botryoidal masses of stalactitic fluorite on crystals of thomsenolite, see lower right part. Dense prosopite is seen in the lower left part. The field of view is 8 cm by 11 cm.
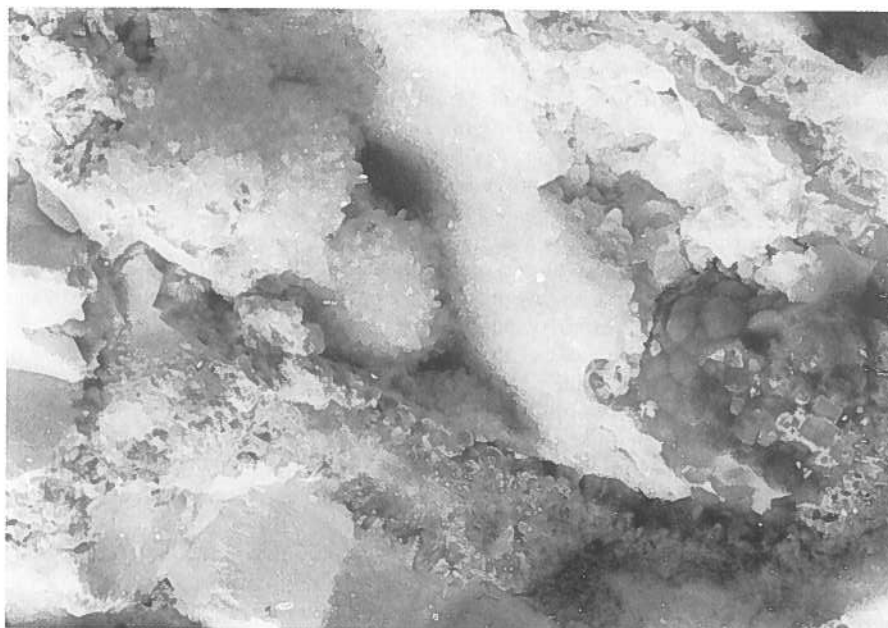
after the formation of ralstonite. Residual solutions gave rise to the jarlite which crystallized on prosopite in cavities and also precipitated gearksutite in other cavities besides allowing wulfenite to form as stray crystals in some cavities.

The variegated spectrum of minerals indicates the activities of complex solutions. The widely varying parageneses in adjacent cavities indicate activities of different solutions in unconnected pockets. The cavities transected by closely spaced, curved lamellae may have originated from highly concentrated solutions of a gel-like character whereas the jarlite crystals sprinkled on the walls of cavities in prosopite may have crystallized from dilute solutions.

The contrast between these prosopite carrying cavernous masses and the prosopite veins is striking: within the latter cryolite was not corroded in the vein breccias and cryolite could recrystallize within the sediment-like prosopite samples. The residual liquid was obviously pure water or a water solution devoid of divalent ions in this case. In passing it may be of interest to mention the occurrence of crystals of cryolite lining fissures in cryolite (Bøggild 1953) because this represents percolation of a similarly pure water phase through the deposit. Alteration of cryolite crystals into thomsenolite and associated minerals indicates later attacks by solutions loaded with Ca, Mg and other cations.

The common thomsenolite paragenesis and prosopite

The alteration of cryolite to thomsenolite has been known from the earliest days of mining at Ivigtut and has been observed in all parts of the cryolite mass. The well known samples contain thomsenolite as the dominating mineral, some samples also contain pachnolite and ralstonite is generally present. Gearksutite as white, powdery or earth-like masses could be found in cavities and fissures together with the other secondary minerals.

These materials typically occurred in solution cavities in cryolite often showing boxwork structures with rectangular shapes derived from the parting directions of the former cryolite (Bøggild 1953). The thomsenolite crystals are usually growing perpendicular to the parting directions indicating dissolution of cryolite and concomitant crystallization of thomsenolite. The solutions involved in these processes were clearly rich in ions of Ca and Mg but small amounts of Sr were also present.

Hydrous solutions with markedly different characters were obviously present within the deposit after the close of Stage 2. Judging by the amounts of products those giving rise to the common thomsenolite paragenesis were dominant. Analyses of cargoes of crude cryolite and of drill cores showed that thomsenolite and associated minerals represented between 2 and 3 % of the cryolite mass or about 80000 tons. Prosopite was not present in the samples of the common thomsenolite paragenesis. The amount of prosopite in the vein brec-

cias and in the cavernous masses exposed in the bottom of the quarry are estimated to be about 200 tons. Samples containing crystals of cryolite, eagerly sought since the 1870's, only numbered a few thousand and cryolite crystals certainly made up less than one ton.

A major part of the cavernous masses carrying prosopite was similar to the common thomsenolite paragenesis. The difference between these masses and the prosopite veins, prosopite appearing as a late mineral in the former but consolidated before thomsenolite in the latter, is thought to result from a mixing of the two types of mineralizations. The explosion-like phenomena giving rise to the fluidized emplacement of debris plus prosopite in the vein breccias may have hit a reservoir or a pocket with Ca-Mg-rich solutions already in an advanced stage of transforming cryolite into thomsenolite and ralstonite. Prosopite precipitated as flint-like, fine grained masses between the ralstonite crystals and the other already formed minerals.

Stalactitic or agate-like fluorite

The stalactitic fluorite observed in these prosopite samples represents a very striking development of this peculiar type of fluorite and was described by Bøggild (1912, 1913) as agate-like crusts. These are generally a few millimetres thick but may be up to a few centimetres thick when forming foliated fissure fillings. They easily split along the foliation presenting curved to mammillary surfaces, up to decimetre across, with a strong pearly luster. Surfaces broken across the crusts show that they are composed of 10 to 15 layers a millimetre, alternatingly translucent and opaque white: the former are clear and the latter are strongly pigmented fluorite as seen in the microscope. Layers of thomsenolite also occur (Bøggild 1913).

Just after the publication by Bøggild (1953), some remarkable samples were collected in the quarry by Niels Sørensen. They showed the agate-like fluorite encrusting crystals of thomsenolite, 1/2 to 1 cm long with square bases 1 or 2 mm across. They look like stalactites because the crusts curve around the prismatic crystals transforming them into cylindrical bodies with bell-shaped terminations. Their colour varies: some are light bluish, some are clear blue and dark purple has also been seen. Broken "stalactites" reveal the square cleavage face of the thomsenolite in their centre (Fig. 20). The intense layering is also present here and the crusts often split along some of the layers leaving spherical impressions in the broken counter-pieces. Inclined, nearly plane cleavage faces can often be seen on the sides of broken "stalactites".

In the electron microprobe the layering appears as an extremely fine grained growth-layering of fluorite, the single layers being less than 1 μm thick. EDX analyses showed Ca dominating, Na, Mg and/or Al present in trace amounts. Sr and S, presumably indicating celestite, were also observed in trace amounts.

X-ray powder diffractograms only indicate the presence of fluorite. Calculations of the analysis given by Bøggild (1913) suggest some ninety per cent of fluorite and a few per cent of ralstonite of an intermediate composition.

The stalactitic fluorite observed in the prosopite samples was of the type just described. Here and there centimetre-wide areas were found to contain fluorite-encrusted fragments of thomsenolite crystals.

The dense, light blue mass of prosopite occurred outside the masses of the stalactitic fluorite but small globules of prosopite crystals were scattered on the walls of some cavities in the fluorite. Fine grained, flint-like prosopite filled some of these cavities. Dispersed in similar fine grained prosopite-fillings there are crystals of fluorite, 15 – 30 μm across. Such small crystals of fluorite have also been observed dispersed in an earth-like precipitate of kaolin from a cavity in agate-like fluorite.

Frequently centimetre-sized, stellate groups of clear, colourless crystals of thomsenolite are found on the mammilary surfaces of cavities in these as well as in the other samples of stalactitic fluorite (Fig. 20).

Bøggild (1913) mentioned signs of brecciation in samples of the agate-like fluorite. Besides the coated fragments of thomsenolite crystals samples of siderite-cryolite where the cryolite is transformed to thomsenolite show pronounced brecciation prior to the deposition of the agate-like fluorite.

Origin of stalactitic, agate-like fluorite

The stalactitic fluorite found in the prosopite samples belongs to the late consolidated products together with the prosopite. Both were followed by crystallisation of thomsenolite in cavities. The peculiar development of the fluorite is regarded as another result of the explosive events through which the prosopite vein breccias formed and prosopite was introduced into a pocket with Ca-Mg-rich solutions in an advanced state of transforming cryolite. The sudden drop in pressure caused the still present solutions to precipitate their loads of dissolved matter probably over an extented period with repeated bursts of water vapour escaping from the system. Crusts of fluorite and of fluorite alternating with thomsenolite, reflect the varying types of dissolved matter in the supersaturated solutions or gel-like masses created in different parts of the system. The cavities in prosopite, transected by closely spaced curved lamellae, fit in with this picture.

After these violent manifestations, there followed a quiet period in which the remaining solutions finally

gave rise to crystallisation of thomsenolite and the other minerals lining the walls of cavities in these masses. The highly varying contents of different cavities underline the lack of connections between the cavities.

Summary of the late stages of the evolution in the cryolite deposit, Ivigtut, South Greenland

Topaz from the cryolite deposit, Ivigtut, South Greenland, is cryptocrystalline, flint-like in thin sections. Pure topaz formed fissure fillings and cement in breccias of cryolite and/or fluorite. Peculiar vein breccias with cryolite fragments embedded in very fine grained fragments of cryolite contain micron-sized aggregates of topaz between the grains. Pure, coarse grained cryolite was transected by millimetre-thin veins of topaz along plane, stepped fractures found to represent planes from the pseudo-octahedron, the pseudo-cube and the pseudo-dodecahedron of the monoclinic but pseudo-cubic mineral. Although cryolite under normal conditions only shows parting along {110} the plane fractures filled by topaz are regarded as cleavage planes caused by explosive events by analogy to the pronounced cleavage in quartz, which forms under these conditions.

The peculiar vein breccias are regarded as veins with fluidized emplacement formed during the explosion-like events. Topaz precipitated from the involved gasses, cryolite was not corroded.

These events took place after consolidation of the pure cryolite (3/4 million tons) the last product from Stage 1 in the evolution of the deposit. The main product from this stage was siderite-cryolite (2.5 million tons).

The solidification of the products from Stage 1 left a residue containing Ca, some Mg, K and a little Sr-Ba besides Al and Si in some sort of F-compounds. Whether O was present alongside these elements or was introduced precursory to the explosion-like events is matter for consideration.

The accumulation of the residue during the evolution of the deposit led to an increasing gas pressure in the cavity containing it. Eventually the roof of the cavity fissured and caving-in of large masses of the cryolite forming its roof took place. Topaz was injected into fissures in still coherent cryolite above the cavity. Ca which made up more than half of the residue started consolidating as colloform and botryoidal masses of fluorite. Repeated bursts injected topaz into these masses. In the lower part of the cavity this led to the formation of the fluorite zone mainly consisting of fluorite and topaz. In the upper parts admixed cryolite from the caving-in of the roof gave rise to the fluorite-cryolite.

These two masses, each about 0.5 million tons, formed in Stage 2. With their consolidation the whole body of fluoride-carrying masses was formed.

Several generations of fluorite are recognized in these masses: fluorite crystallized before topaz, alternating with and, finally, after topaz. This late fluorite contained small cavities in which prosopite sometimes grew on the crystal faces of the fluorite.

Mg, K and Sr-Ba formed minerals of their own. Weberite crystallized before and contemporaneously with the late fluorite. "Ivigtite", jarlite and other Sr-Ba fluorides formed together with and after the late fluorite. Ba-Sr sulphates accompanied these fluorides. In the fluorite-cryolite fissures were filled by jarlite-carrying aggregates rich in crystal-lined cavities. Cryolite, hither-to stable, was here dissolved and replaced by the Sr-minerals.

Throughout the solidified masses (from Stage 1 and 2) fluids, expelled during Stage 2, collected in fissures and isolated cavities. They were solutions rich in Ca with some Mg and a little Sr. Dissolving cryolite they gave rise to cavities with crystals of thomsenolite, pachnolite some ralstonite and here and there gearksutite. These products represent Stage 3, the final stage in the development of the Ivigtut deposit.

In an early phase of Stage 3 prosopite was introduced in vein breccias closely resembling the vein breccias with topaz. As these the prosopite vein breccias are regarded as products of explosion-like events though of rather limited extent. The cryolite fragments in the prosopite vein breccias are not corroded but in places showed recrystallisation and crystals of cryolite were observed in small cavities indicating residual solutions not carrying Ca and Mg.

The explosion-like events also introduced prosopite into cavities where solutions were at work transforming cryolite to thomsenolite and ralstonite. Stalactitic or agate-like fluorite arose in such surroundings presumably because release of water vapour left supersaturated or gel-like masses instead of the Ca-rich solutions. Another result of the release of water vapour is seen in the presence of cryolite crystals in fissures where they obviously formed from perculating, pure water.

Acknowledgements

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