THE CYPRIN—THULITE DEPOSIT AT ØVSTEBØ, NEAR KLEPPAN IN SAULAND, TELEMARK, NORWAY

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Introduction

The deposit to be discussed in the present paper is situated as shown in Figs. 1 and 2 near the farm Øvstebø not far from Kleppan in the district of Sauland in the county of Telemark in Southern Norway. The locality has earlier been given partly as Kleppan and partly as Sauland or Souland (old spelling). It is the type locality for cyprin (blue var. of vesuvianite) which was described by BER-ZELIUS in 1820, and for thulite (red var. of zoisite) described by BROO-KE in 1823. The first to publish any information about the deposit as such was Scheerer in 1845; BRØGGER gives a crystallographic description of thulite in 1879, and WERENSKIOLD has a sketch map and a profile of the Øvstebø deposit in his paper on the geology of Eastern Telemark in 1909 (p. 51).

Geology.

The district of Sauland is part of the huge area in Southern Norway made up of the Precambrian supracrustal rocks of the Telemark formation: acid lavas (quartz porphyries and rhyolites), basic lavas, tuffs, agglomerates, quartzites, and arkoses. These rocks have been

intruded by gabbroic sheets, which are now found as amphibolites usually concordant to the supracrustal rocks, and it may in individual cases be difficult to decide if they are intrusive or extrusive.

The whole rock series has been strongly folded as shown in Fig. 2. The Gausta syncline and the Bleka anticline have been mapped in detail during recent years but the results have not been published so far. The detailed mapping has not reached the district of Sauland but the architecture is most probably in its broad features as shown in Fig. 2.

The rocks of the Telemark formation have to a great extent been granitized, and are, where they are not cut off by faults or disappear under the Caledonides, surrounded by — and are certainly underlain by — the younger Telemark granite (or Telemark gneiss). They are nearly everywhere metamorphosed, in the amphibolite facies close to the Telemark granite, and further away from the granite in the epidote-amphibolite facies or in the greenschist facies. In the Øvstebø —Kleppan area the rocks are found in the epidote-amphibolite facies.

Fig. 3 is a sketch map of the geology of the immediate surroundings of Øvstebø. The strike varies somewhat but averages N 70° W with a steep northerly dip. The predominating rocks are quartz porphyry and agglomerate. The quartz porphyry is light gray with phenocrysts of quartz and feldspar, mainly albite. The phenocrysts are about 1 mm across, while the groundmass is very finegrained, usually with submicroscopic grains, indicating that the porphyry was originally a glassy rock. Sericite and epidote as alteration products are common constituents of the quartz porphyry.

The agglomerate is made up of bigger and smaller angular lava fragments in a very fine-grained groundmass, and has often a green colour because of epidotization. Small blebs and masses of red calcite are quite common and widespread in this rock. North of Øvstebø the agglomerate attains an apparent width of at least 1 000 m. Stratigraphically it corresponds most probably to the zone of tuffs and agglomerates described by D. WYCKOFF (1933) from Gausta and Rjukan waterfall.

A number of amphibolites in the surroundings are all concordant to the supracrustal rocks. On the basis of the results of the detailed
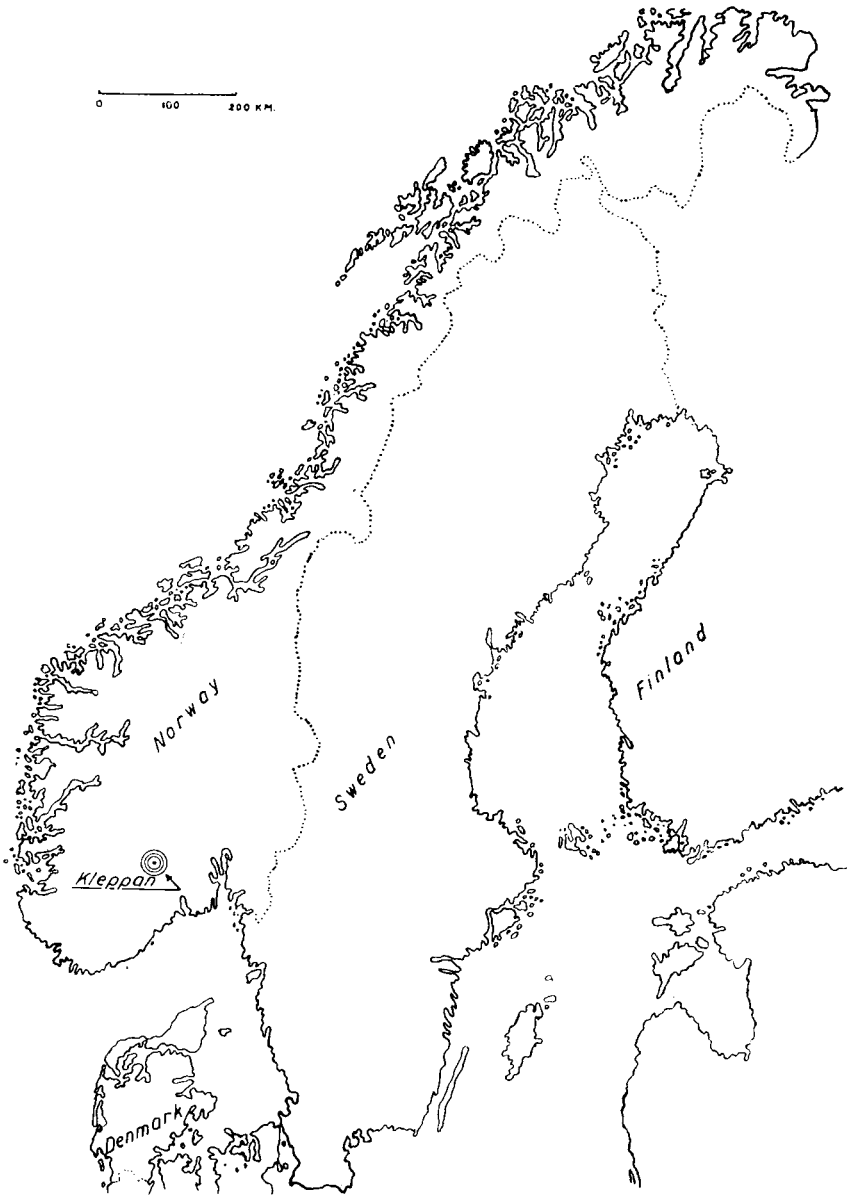
Fig. 1. Map showing situation of Kleppan.

mapping of the Bleka anticline and in the Gausta area they should most probably be interpreted as metamorphosed basic intrusives and not as original lavas. The amphibolites are medium grained, and consist of amphibole, albite, and epidote-clinozoisite.

Pegmatite dykes are not uncommon in this area. They contain feldspar, quartz, and mica, and so far only hematite and epidote have been found as accessory minerals. As seen in Figs. 3 and 4 one of them cuts the cyprin- and thulite-bearing quartz vein.

The nearest exposures of granite are quite a distance from Øvstebø, as shown in Fig. 2. It is of course impossible to make any definite statement about the distance to the underlying granite. The grade of metamorphism, however, indicates that the granite is not too close to the present surfaces.

The mineral assembly or parts of the complete assembly to be discussed in this paper is found in 6 places. The localities are indicated in Fig. 3, and will be referred to as numbers 1—6.

No. 1 is the main occurrence of cyprin, thulite, etc., and is the one which has been known for a long time, while the other minor ones have been found during the course of the present investigations. A sketch map of the deposit is presented as Fig. 4. The big quartz vein which forms deposit No. 1 is emplaced parallel to the strike of the country rocks, and contains all the minerals to be described below with the exception of tremolite. Some blasting has been done, probably in search of valuable minerals, in two places indicated by O in Fig. 4. The bedrock is unfortunately widely covered by drift, impeding a detailed investigation of structural relationships. A possible zoning of the vein, for example, may have escaped observation.

At localities 2 and 3 a number of quartz lenses are found, which may attain a length of 1 meter or more. Locally they contain thulite, cyprin, tremolite and calcite. The bedrock is an epidotized agglomerate with a somewhat variable strike about NNW and with an easterly dip of about 45°. Small pegmatite veins or lumps are common; they are mostly emplaced parallel to the schistosity of the agglomerate but crosscutting structures are not unusual. A sketch from No. 3 is presented as Fig. 5.

At the place marked No. 4 on the map the agglomerate is coloured red over a small area by an impregnation of thulite. Quartz has been
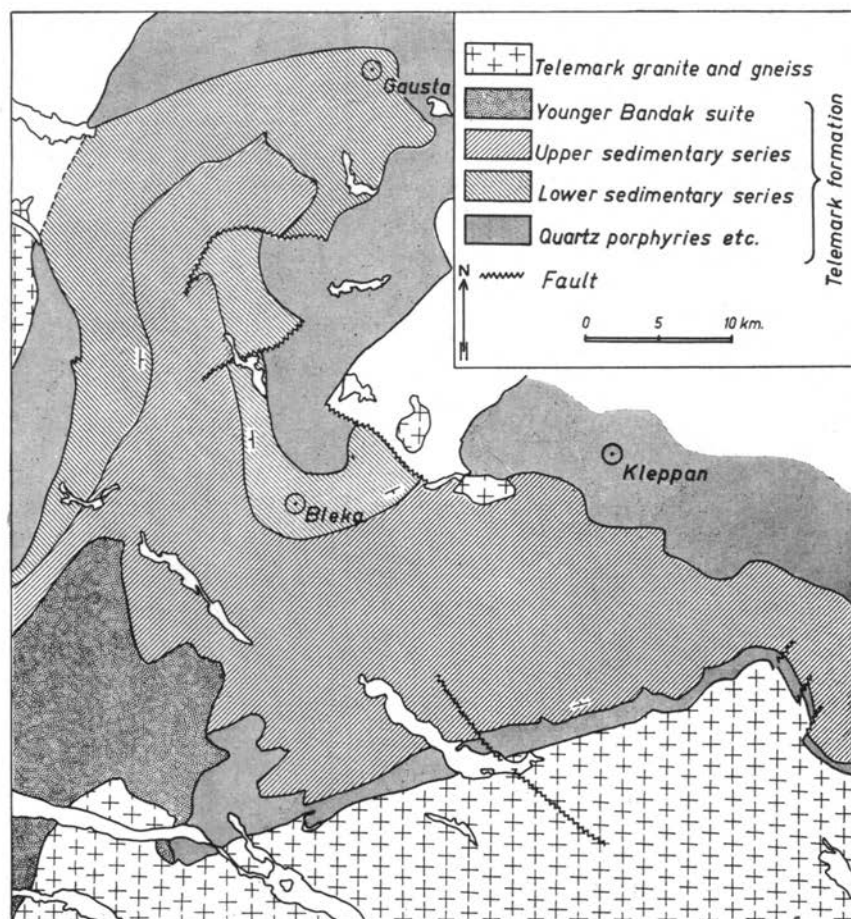
Fig. 2.   Geological map of a part of the Telemark formation.

introduced at the same time, but true quartz masses have not been formed.

Deposit No. 5 is a quartz vein or elongated lens of quartz quite rich in tremolite and scapolite, and with some thulite. Cyprin has not been found in this vein.

At locality No. 6 cyprin, thulite, and grossularite together with quartz are found in cavities in amphibolite close to its contact with quartz porphyry.
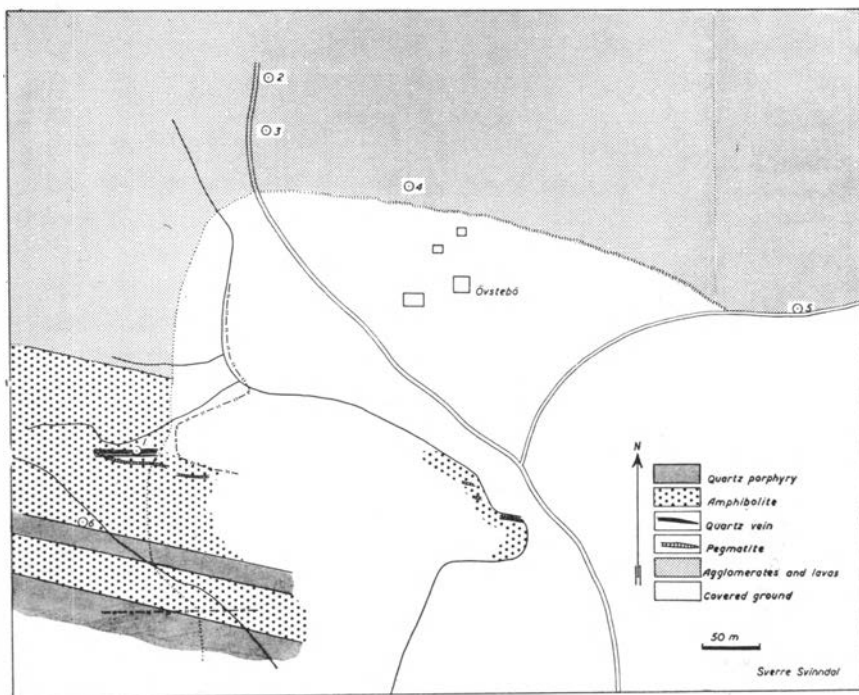
Fig. 3. Geological map of the surroundings of Øvstebø near Kleppan. The mineral occurrences discussed in the text are numbered from No. 1 to No. 6.

It is worthy of notice that the cyprin — thulite — etc. paragenesis is found in different kinds of bedrock, in No.'s 2, 3, 4, and 5 in quartz porphyry, in No. 6 in amphibolite, and in No. 1 on the contact between amphibolite and quartz porphyry.

Description of the minerals.

Fluorite.

Fluorite is quite common. It varies in colour from colourless to a deep blue. An optical spectrogram showed nothing of interest apart from some Mg and traces of Fe and Mn which may be due to impurities.
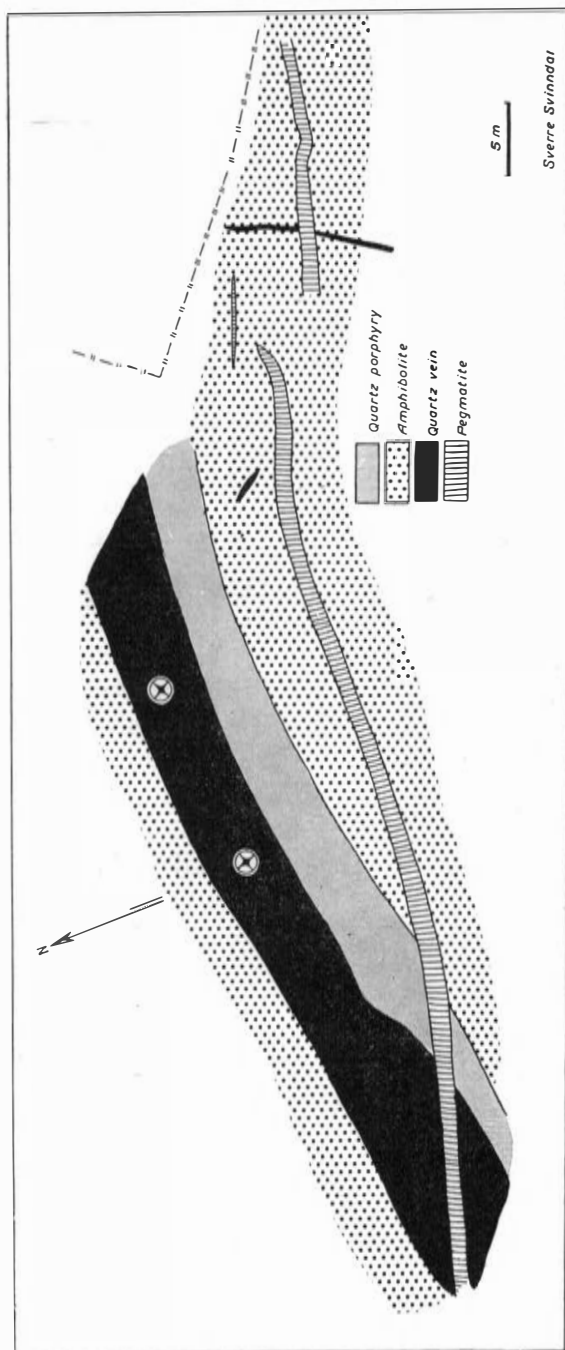
Fig. 4. Detailed geological map of the main cyprin-thulite occurrence. (No. 1 of Fig. 3).
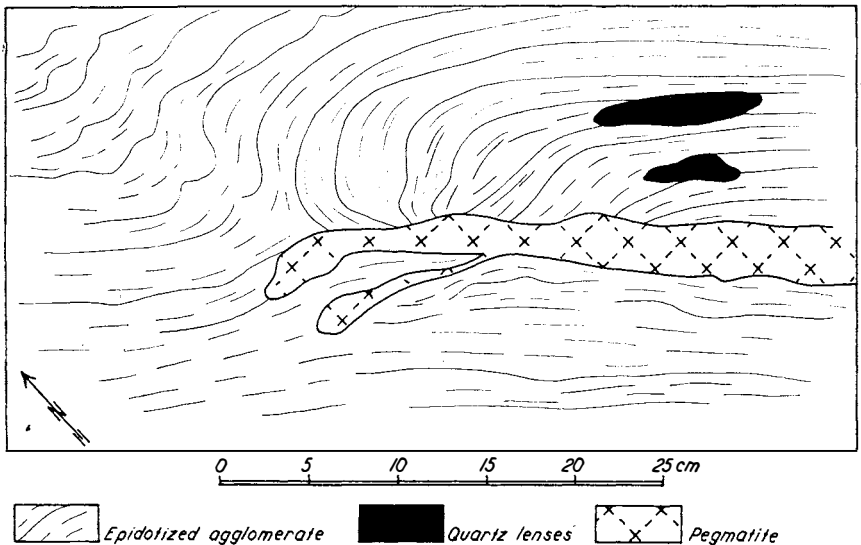
Fig. 5. Sketch map from cyprin — thulite occurrence No. 3. (See fig. 3).

Hematite.

Hematite is the only opaque mineral found in Sauland so far. It is not very common, but is found now and again together with and in the same way as the other minerals.

Quartz.

Quartz is the dominating mineral in all deposits, occurring to the extent of at least 80 percent. An optical spectrogram shows traces of aluminium.

Calcite.

Calcite is quite common, but is probably less common than fluorite, and very subordinate compared to quartz. An optical spectrogram taken by Mr. S. RUTLIN shows some magnesium but no traces of rare earth elements.
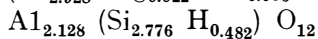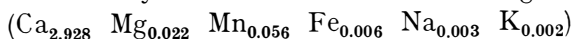
Scheelite.

Scheelite has so far been found in a few specimens only from deposit No. 1. It occurs intimately associated with quartz, thulite, epi-

dote, cyprin, grossularite, fluorite, calcite and desmin. The fluorescence colour in short wavelength ultraviolet light is a pure white, perhaps with a slight tinge of yellow, indicating a content of about 0.7 percent molybdenum (HORNE 1951). An optical spectrogram shows in addition to Ca, Wo, and Mo traces of Al and Be. To the authors' knowledge Be has not earlier been reported in scheelite.
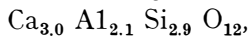
Grossularite garnet.

Grossularite is of common occurrence in the association grossularite, cyprin, thulite, fluorite, quartz. The colour varies from a pure white to a very light greenish yellow or brownish yellow. The crystals which can attain a size of one cm across are bounded by (110), with occasional development of (100) faces.

The chemical composition is shown in table No. 1. A calculation of the analysis on the basis of twelve O's gives the following formula:
$$(Ca_{2.928} \ Mg_{0.022} \ Mn_{0.056} \ Fe_{0.006} \ Na_{0.003} \ K_{0.002})$$
$$Al_{2.128} \ (Si_{2.776} \ H_{0.482}) \ O_{12}$$
which, if Mg, Mn, Fe, Na, and K is replaced by Ca, and 4 H by Si is
$$Ca_{3.0} \ Al_{2.1} \ Si_{2.9} \ O_{12},$$
in close agreement with the ideal formula of grossularite, $Ca_3 \ Al_2 \ Si_3 \ O_{12}$.

In terms of molecular percent of the pure garnet «molecules» the composition is:

93.2 mol percent grossularite.
   4.0   —   tricalcium aluminate hexahydrate.
   1.9   —   spessartite.
   0.7   —   pyrope.
   0.2   —   almandine.

The edge length (a) of the unit cell was determined and found to be 11.855 ± 0.010 Å. As first pointed out by STOCKWELL (1927) and later confirmed by others a linear relationship exists between edge lengths and chemical composition within the garnet group (a slight deviation in the hydrogrossularite series has been demonstrated by YODER (1950)). After minor corrections for the content of the other garnet «molecules» in the Sauland grossularite the edge length of pure grossularite is calculated to
$$a = 11.835 \pm 0.010 \text{ Å.}$$

The specific gravity of the analyzed material is 3.567. If this value is adjusted in the same way as above, the specific gravity of pure grossularite is calculated to
$$\text{sp.g.} = 3.598.$$
The specific gravity calculated from the above value of a is for pure grossularite
$$\text{sp. g. }_{\text{calc.}} = 3.584.$$
The refractive index is $n_{Na} = 1.719 \pm 0.002$
which recalculated as above gives a value for pure grossularite of
$$n = 1.722 \pm 0.002$$
a value which is about 0.02 lower than what would be expected from data published earlier (H. S. YODER, 1950).

An optical spectrogram taken by Mr. S. RUTLIN shows lines of Ti, V and Ga in addition to the major components. The V content was roughly estimated by Mr. RUTLIN to O.x percent which is a surprisingly high figure for a grossularite.

Colour and refractive index vary considerably from specimen to specimen and from crystal to crystal. A pure white grossularite gave $n = 1.727 \pm 0.002$, and a yellow variety from the same specimen $n = 1.733 \pm 0.001$.

E p i d o t e (*Clinozoisite*).

Epidote occurs in a somewhat different way from the other minerals, as it is usually found in lumps and variously shaped finely crystalline masses which are probably formed by replacement of inclusions of wallrock. More often than not they are surrounded by a not too well defined rim of grossularite varying in width from zero to two centimeters.

The colour of the Sauland epidote varies from a light green to a fairly dark green.

P i e d m o n t i t e (*Manganiferous clinozoisite*).

Piedmontite has been identified by its characteristic colour and x-ray powder pattern. It resembles thulite but is more brownish red, as opposed to thulite's pink to rose red. It occurs together with, and in the same way as, thulite, but is less common.

T h u l i t e (*Pink zoisite*).

Thulite of a lively pink to rose colour is common in the association thulite — grossularite — cyprin — quartz — calcite — fluorite. It is mostly massive but good crystals are also found; in fact W. C. BRØGGER (1879) determined the axial ratios and solved the problems of the crystallography of zoisite on perfect crystals of thulite from Sauland.

The chemical composition is given in table No. 1. The amount of manganese is surprisingly low. It is nevertheless believed that trivalent manganese is the cause of the pink colour. No attempt has been made to actually determine by experiment the valence state of this element because of the experimental difficulties involved, the content of Mn_2O_3 being only 0.34 percent and with divalent as well as trivalent iron present in the same mineral.

A calculation of the analysis on the basis of 13 oxygen atoms gives the following result $Ca_{2.00}$ $Al_{2.84}$ $Fe^{III}_{0.18}$ $Mn^{III}_{0.02}$ $Fe^{II}_{0.08}$ $Si_{2.97}$ O_{13} $H_{0.86}$. On the assumption that Fe and Mn replace Al this gives the formula

$$Ca_{2.0}\ Al_{3.1}\ Si_{3.0}\ O_{13}\ H_{0.9}$$
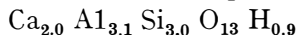
in fair agreement with the theoretical formula.

The specific gravity of the analyzed material is 3.38, and the refractive indices $\alpha_{Na} = 1.700 \pm 0.001$, $\beta_{Na} = 1.703 \pm 0.001$, and $\gamma_{Na} = 1.708 \pm 0.002$. The mineral is biaxial positive with $+ 2V = 71° \pm 1°$, and is a β-zoisite with the optic plane normal to (010). It is somewhat surprising that the Sauland thulite with an iron-content of only 3.06 percent Fe_2O_3 is β-zoisite, and with an axial angle as high as 71°.

The physical properties vary considerably from specimen to specimen. The data given above are determined on the analyzed material, which, to ascertain homogenity, was produced from a number of large crystals from one and the same specimen by a heavy liquid separation.

C y p r i n (*Blue vesuvianite*).

Cyprin is of common occurrence in the association cyprin-thulite-grossularite-quartz-calcite-fluorite. It is usually well crystallized but is very easily broken and good crystals are therefore difficult to obtain. The colour is a deep sky-blue, but varieties which are greenish

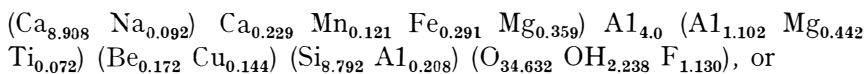blue to bluish green are very common. The name cyprin was given to the Sauland vesuvianite by J. J. BERZELIUS (1820) in allusion to its blue colour. He proved the presence of copper by a blowpipe analysis and ascribed the blue colour to the presence of that element.

An analysis of cyprin is given in Table No. 1. WARREN and MODELL (1931) give the following general formula of vesuvianite $Ca_{10}Al_4(Mg, Fe)_2Si_9O_{34}(OH)_4$, and point out that there are two sets of tetrahedral positions in the structure, usually empty, one of which is probably responsible for the accomodation of the occasional content of Be in vesuvianite. MACHATSCHKI (1932) has remarked that one of the 10 Ca ions has a unique position, which is really somewhat too restricted for the big Ca ions, and he gives evidence for a tendency towards accomodation of the smaller Mg ions in this position. Taking Machatschki's remarks into consideration, the formula may be re-written in the following way:

$$X_9(X, Y)Y_4Y_{2-x}E_xZ_9(0, OH, F)_{38}$$
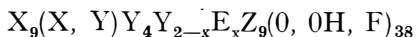
where X stands for the big ions (Ca, Na, K), Y for the medium sized ions (Mg, Mn, Fe, Al), Z for Si (which can, to some extent, be replaced by Al), and E for ions in one of the two sets of usually empty tetrahedral positions.

A calculation of the analysis on the basis of 38 ozygens gives the following result:

$(Ca_{8.908}\ Na_{0.092})\ Ca_{0.229}\ Mn_{0.121}\ Fe_{0.291}\ Mg_{0.359})\ Al_{4.0}\ (Al_{1.102}\ Mg_{0.442}\ Ti_{0.072})\ (Be_{0.172}\ Cu_{0.144})\ (Si_{8.792}\ Al_{0.208})\ (O_{34.632}\ OH_{2.238}\ F_{1.130})$, or

$X_9(X,Y)Y_4Y_{2-0.40}\ E_{0.32}\ Z_9(O, OH, F)_{38}$, a result which is very close to the crystallographically established formula.

Cu has tentatively been placed with Be in the vacant tetrahedral positions. The content of Cu is too low to make possible a direct location of that element.

The specific gravity of the analyzed material is 3.421, in good agreement with data published elsewhere.

The mineral is uniaxial negative with

$$\omega_{Na} = 1.705 \pm 0.002 \text{ and } \varepsilon_{Na} = 1.697 \pm 0.002.$$

The values given by LARSEN (1934) for cyprin are higher by 0.008.

Diopside.

Diopside is very rare, and has so far been found in one specimen only from the upper trial in deposit No. 1, where it occurs associated with epidote, thulite, cyprin, and grossularite. The colour is a pure white, perhaps with a slight tinge of yellow. The mineral gives the characteristic x-ray powder pattern of the diopside-hedenbergite series. It is biaxial positive with $a_{Na} = 1.671 \pm 0.003$, $\beta_{Na} = 1.679 \pm 0.002$, and. $\gamma_{Na} = 1.702 \pm 0.003$. The specific gravity is 3.30 ± 0.01. These data are characteristic of a diopside with an approximate composition $Di_{90}He_{10}$.

Tremolite.

Tremolite is rather rare. It occurs in white needles together with scapolite in deposit No. 5, and was identified by its characteristic x-ray powder pattern. A green variety, apparently a more iron-rich member of the tremolite-actinolite series is found in quartz in deposit No. 1.

Oligoclase.

Feldspar is quite rare in the Sauland deposits. A specimen from deposit No. 1 has stringers and blebs of oligoclase in quartz, with $a_{Na} = 1.542 \pm 0.002$, $\beta = 1.546 \pm 0.001$, $\gamma = 1.550 \pm 0.002$, and 2 V — was estimated to 85°. The optic data correspond to an oligoclase of composition Ab_{74} An_{26}.

Scapolite.

Scapolite is of rare occurrence and is found in any amount only in deposit No. 5, where it occurs intimately associated with thulite. It is uniaxial negative with high birefringence and $\omega = 1.592 \pm 0.001$, corresponding to a calcium-rich scapolite of composition Me_{77} Ma_{23}.

Desmin.

Desmin is rare and has been found in deposit No. 1 only. It occurs in radiating bundles of pure white needles, associated with thulite and cyprin and in one specimen also with scheelite. $\beta_{Na} = 1.497$, and the identification was confirmed by an x-ray powder pattern.

Paragenesis.

A complete list of the minerals found at Sauland is given below. The formulae are somewhat simplified, taking into consideration only the major chemical components.

Quartz SiO_2

Thulite $Ca_2Al_3Si_3O_{12}OH$

Epidote   —»—

Piedmontite —»—

Grossularite $Ca_3Al_2Si_3O_{12}$

Cyprin $Ca_{10}Al_4Mg_2Si_9O_{34}(OH)_4$

Diopside $CaMgSi_2O_6$

Tremolite $Ca_2Mg_5Si_8O_{22}(OH)_2$

Scapolite $Ca_4Al_6Si_6O_{24}CO_3$

Oligoclase $(Na, Ca)Al(Si, Al)_3O_8$

Desmin $Ca_2NaAl_5Si_{13}O_{36} \cdot 14H_2O$

Hematite Fe_2O_3

Calcite $CaCO_3$

Fluorite CaF_2

Scheelite $CaWO_4$

Quartz represents the bulk of the deposit. The next most common minerals are thulite, epidote, piedmontite, grossularite and cyprin, followed closely by fluorite. Calcite is subordinate compared to fluorite, and the other minerals are even less common than calcite.

As demonstrated by the list above we are dealing with an assembly of calcium minerals rich in aluminium, and with some magnesium. During the formation of the minerals SiO_2 and probably also H_2O were present in excess. The mineralizing medium also contained appreciable amounts of fluorine and some carbon dioxide.

If the deposit be considered from the point of view of the phase rule, the number of phases are 14. Epidote and piedmontite are counted as one phase only as they are really one species, the only difference between them being a lower or higher content of manganese. The chemical components are

SiO_2 CaO MgO Na_2O Al_2O_3 Fe_2O_3 CO_2 F and WO_3.

OH has not been counted as a component because the minerals have most probably been in equilibrium with H_2O during their formation,

manganese has not been counted as it plays no independent role in the formation of any of the minerals, but replaces aluminium or calcium. A possible content of C1 in the scapolite has not been taken into consideration, as the scapolite is a carbonate scapolite quite close to mejonite in composition. The number of components is therefore 9, and we find in this mineral assembly 14 phases and 9 components in contradiction to the mineralogical phase rule which states that in any mineral deposit in equilibrium the number of phases equals the number of components. The deposit as a unit was therefore not in equilibrium during its formation, a statement which may be put in a different way, namely that the deposit during its formation did not consist of one single chemical system but of a number of chemical systems.

The chemical components may be paired off with the occurring minerals as follows

SiO_2 Quartz
CO_2 Calcite
F   Fluorite.
WO_3 Scheelite
Fe_2O_3 Hematite
Na_2O Oligoclase and Desmin.
CaO
MgO Thulite, Epidote, Grossularite, Cyprin, Diopside, Tremo-
Al_2O_3 lite, and Scapolite.

The two sodium minerals oligoclase and desmin never occur in one and the same specimen. In accord with the above statement conditions have apparently been such that in some parts of the deposit oligoclase has been the stable sodium mineral, in other parts desmin.

The three components CaO MgO and Al_2O_3 are responsible for the existence of 7 minerals. Of these thulite, epidote (or piedmontite), grossularite and cyprin very commonly occur in intimate association. The curious coexistence of zoisite and clinozoisite (thulite and epidote) was noted already by W. C. BRØGGER (1879). When either tremolite or scapolite is present one of the above mentioned minerals always seems to be absent. In deposit No. 5 where tremolite and scapolite occur together neither cyprin nor grossularite have been found.

As mentioned in the descriptive part of this paper most of the minerals vary considerably in physical properties and chemical composition from specimen to specimen and even from crystal to crystal. This phenomenon is just as much a proof of nonequilibrium conditions during the formation of the deposit as the existence of super-numerary phases.

Genesis.

The mineral assembly found in Sauland would be characteristic for a contact-metasomatic impure limestone in the inner contact zone. Such a mode of formation is, however, out of the question in this case. There is no trace of limestone in the bedrocks, in fact the complete absence of limestone layers is typical for the supracrustal rocks of the Telemark formation (apart from a thin limestone in the younger Bandak suite of rocks, but that is irrelevant to the present problem). Also, there is no granite or other plutonic rock in the immediate neighbourhood, nor are there any indications of a granite close by in depth.

The predominance of quartz together with fluorite and some calcite would be quite normal in a hydrothermal vein. The complete mineral paragnesis, however, and especially the existence of minerals like scapolite, diopside, tremolite, and vesuvianite render impossible the interpretation of the deposit as a hydrothermal vein in the conventional sense of this term.

As discussed above the deposit is in a state of non-equilibrium, a phenomenon which must be accounted for by its mode of formation. The PTX conditions must have been different in different parts of the deposit when the several minerals were formed. A difference in pressure or temperature in this small-sized deposit would necessarily imply a difference in time, and hence the existence of several generations of minerals. There are no signs of that at all; on the contrary, structural and textural observations indicate that all minerals were formed contemporaneously. We are, therefore, compelled to accept a difference in the chemical composition in different parts of the deposit at the time of formation. Such a state of affairs can be explained if the mineral assembly under discussion be interpreted as the products

Table 1. *Analyses in weight percent of minerals from the Øvstebø deposit. A: Thulite. Analyst* BR. BRUUN. *B: Grossularite. Analyst* BR. BRUUN. *C: Cyprin. Analyst* BR. BRUUN. *D: Cyprin. Analyst* G. LINDSTRØM (1888).

	A	B	C	D
SiO_2	38.46	37.20	36.9	37.90
TiO_2	tr.	—	0.4	0.26
Al_2O_3	31.20	24.21	18.9	19.47
Fe_2O_3	3.06	⎧ 0.09	⎧ 1.1	0.40
FeO	1.25	⎩	⎩	0.21
MnO		0.88	0.6	0.91
Mn_2O_3	0.34			
MgO	0.01	0.20	2.2	2.17
CaO	24.17	36.65	35.8	36.06
Na_2O	0.04	0.02	0.2	0.14
K_2O	0.01	0.02	0.01	0.11
H_2O-110°.	0.03	0.02	0.03	⎧ 0.67
H_2O^+	1.67	0.97	1,41	⎩
CuO	n.d.	n.d.	0.8	0.73
BeO	n.d.	n.d.	0.3	n.d.
F	n.d.	n.d.	1.5	1.72
—0 for F			0.6	0.72
Sum	100.24	100.26	99.5	100.03

of reaction between bedrock and slowly moving solutions or material transported by diffusion to the site of reaction. If the movement of the mineralizing medium is sufficiently slow as it reacts with the bedrock, it may easily acquire a different chemical composition in different parts of the deposit giving rise to variation in the reaction products. This interpretation would seem quite feasible if it were confirmed by other observations. That is not the case, however. The finegrained lumps of epidote described above are in all probability altered inclusions of bedrock. Transitional stages between the fine-grained epidote lumps and the coarsegrained masses of quartz-thulite-cyprin-grossularite have never been found, nor are there in the deposit any palimpsest structures of the bedrock or any traces of «ghostly remnants».

In the case of a contact-metasomatic grossularite-vesuvianite-fluorite deposit the source of the chemical constituents is fairly obvious. In the present case the problems are much more complicated. The deposit is situated in a regionally metamorphosed and granitized area, and it can only in a general way be referred to the mobilization of ions during the process of regional metamorphism and granitization. A thorough study of the petrology of the rocks of the area may shed some light on the formation of the deposit under discussion. With the pressent knowledge of the petrogenesis of the local rocks and the present understanding of processes of mineral formation in general, a number of problems concerning the genesis of the Sauland deposits must be left unsolved.

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