DE DANSKE NÛGSSUAQ EKSPEDITIONER 1938–39

UNDER LEDELSE AF ALFRED ROSENKRANTZ

GRØNLANDS GEOLOGISKE UNDERSØGELSE

XONOTLITE-, PECTOLITE- AND NATROLITE-BEARING FRACTURE VEINS IN VOLCANIC ROCKS FROM NÛGSSUAQ, WEST GREENLAND

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WITH 6 FIGURES IN THE TEXT AND 1 PLATE

Contents

Abstract

Fracture veins containing calc-silicate and zeolite minerals are developed in tuff, pillow lava and olivine basalts from the West Greenland basaltic province. The minerals in the veins can be grouped into three distinct suites, each of which is characterized by one dominant mineral. The minerals are xonotlite, pectolite and natrolite. The suites are developed at different horizons in the volcanic sequence, the lowest being the xonotlite suite, followed by the pectolite suite and uppermost, the natrolite suite. The mineral suites are believed to have been formed from hydrothermal solutions at around 300°C and at pressures less than 300 bars. These solutions may have been of magmatic origin, possibly mixed with percolating sea water. It is thought that the suites crystallized in systems at equilibrium under temperature conditions corresponding to the upper zeolite and lower greenschist metamorphic facies.

Introduction

In the spring of 1962, Professor H. Sørensen of the Mineralogical Museum, Copenhagen, let the author have some samples containing zeolites and calc-cilicate minerals for examination. They were gathered by H. Rink in the middle of the last century. Later, Professor A. Rosenkrantz of the Mineralogical Museum, Copenhagen, let the author have some similar material gathered by the Nûgssuaq Expeditions in 1938 and 1939, and by the Geological Survey of Greenland after World War II.

The minerals are developed in fracture veins cutting tuff, pillow lava and basalt of the West Greenland basaltic province (figs. 1 and 2).

The West Greenland basaltic province and the stratigraphic position of the fracture veins

The volcanic activity in West Greenland began in the Lower Danian and is represented by tuff horizons in marine sediments. The marine sedimentation continued and in the Upper Danian new fossil-rich tuff horizons were formed, followed by volcanic formations (Rosenkrantz and Pulvertaft, in press). The lower part consists of submarine layers (pillow lavas) of variable thickness up to 500 metres, followed by plateau basalts of several kilometres thickness. These can be separated into three series: a lower series of olivine basalts, a middle series of plagioclase-porphyritic olivine basalts, and an upper series of olivine-free basalts.

Fracture veins with zeolites and calc-silicate minerals are developed only in the submarine layers and in the olivine basalts. The veins rarely have a width greater than 10 centimetres. Within the area around Marrait (fig. 3), from which abundant material was gathered, only the submarine series and the olivine basalts are developed. The major part of the vein material was taken *in situ* from the basalts, a minor part being taken from gravel deposits on the beach. A detailed geological mapping of the area was carried out during the summer of 1964 by K. Binzer, S. Skytte and K. Strand-Petersen. Because of the faulting and discontinuous exposure of the mapped volcanics, a stratigraphic correlation of these was difficult to undertake.
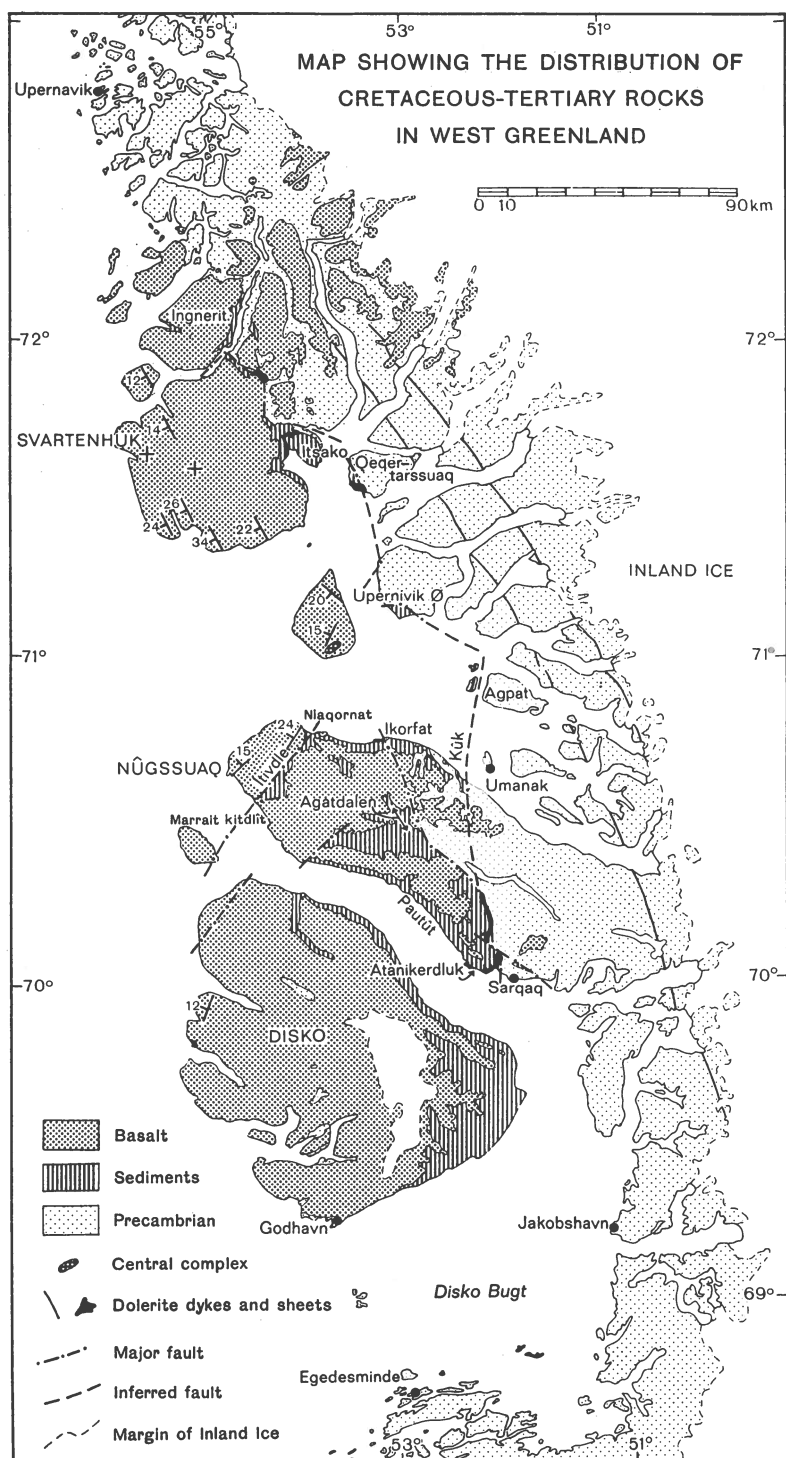
Fig. 1. Geological map showing the West Greenland basalt province (from ROSEN-KRANTZ and PULVERTAFT, in press).

Fig. 2. Pectolite-bearing fracture veins cutting olivine basalts. The veins are more resistant to weathering and decomposition than the basalts and stand out as narrow ridges. Locality 3 in fig. 3. (Photo K. BINZER, GGU).

The vein material can be classified into three mineral suites, each characterized by one dominant mineral. The minerals are xonotlite, pectolite, and natrolite.

The three mineral suites are characteristic of certain levels in the basalts of the Marrait area. The xonotlite suite is developed in the lowest horizons and is only found in the submarine layers, the tuffs, and the pillow lavas. Above it is the pectolite suite which is found in both submarine layers and olivine basalts; uppermost, the natrolite suite is developed only in olivine basalts.
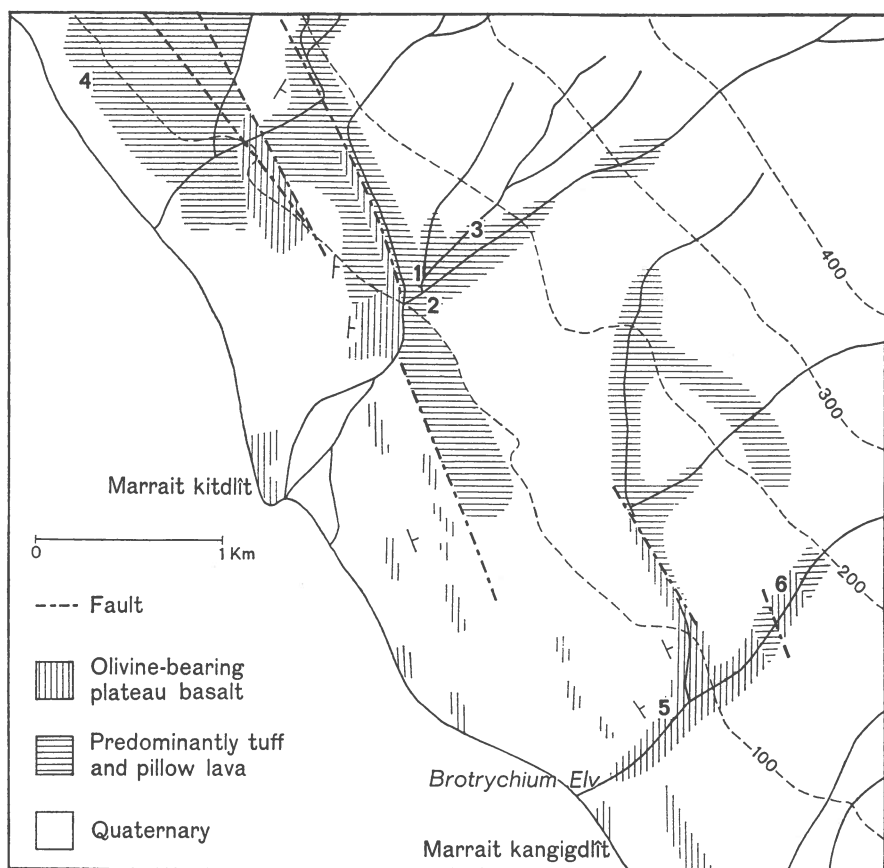
Fig. 3. Geology of the Marrait area (after K. BINZER, S. SKYTTE and K. STRAND-PETERSEN).

Source of the material studied

RINK (1853) described some zeolites and calc-silicate minerals present in fracture veins in badly weathered basalts. Among these minerals RINK distinguished between an asbestos-like okenite and an okenite with radiating cleavage.

The asbetos-like okenite was investigated by BØGGILD (1953). With some reservation he described it as a wollastonite. Later, SØRENSEN (1956) identified the mineral as xonotlite.

RINK mentioned that okenite with radiating cleavage is dull and opaque in appearance and is found together with the asbestos-like okenite in fracture veins. The investigation of RINK's material, carried out by the author, has shown that the variety is probably identical

with pectolite. Pectolite from Marrait has been mentioned briefly by SØRENSEN (1956).

The Mineralogical Museum of Copenhagen possesses about fifty samples gathered by RINK from the Marrait area. The exact locality is unknown. However, the discovery of similar material during the summer of 1964 indicated that the locality is probably around Marrait kitdlît, at location 1, fig. 3. The major part of the material gathered by RINK belongs to the xonotlite suite. A few samples were taken from a gravel deposit.

During the Nûgssuaq Expeditions of 1938 and 1939 led by Professor A. ROSENKRANTZ, both xonotlite and pectolite samples were gathered from the north coast of Nûgssuaq at Niaqornat (fig. 1).

After World War II, during the Geological Survey's expeditons of 1947, 1961 and 1964, under the direction of Professor A. ROSENKRANTZ, material containing xonotlite and pectolite was gathered from the area around Marrait. Samples with xonotlite were gathered at locations 1 and 2, fig. 3 and samples with pectolite were gathered at locations 3, 4 and 5, fig. 3. A few samples were taken from gravel deposits.

Natrolite from Marrait was described by RINK (1853). The exact location is unknown and no samples containing the mineral were preserved.

During the summer season of 1957, also under the direction of Professor A. ROSENKRANTZ, a considerable amount of material containing natrolite was gathered *in situ*, in basalt at location 6, fig. 3.

## Mineral descriptions

Xonotlite

BØGGILD (1953) described the asbestos-like okenite as a wollastonite. However, he pointed out that the mineral has only positive elongation. As mentioned above, SØRENSEN (1956) has identified the mineral as xonotlite and has determined its optical data. According to SØRENSEN the refractive indices of the mineral are $n_x = 1.582 \pm 0.002$, $n_y = 1.582 \pm 0.002$ and $n_z = 1.592 \pm 0.002$.

The mineral is white to pale grey, sometimes with a pink lustre. It is monoclinic and optically positive with a small 2V. It is fibrous with cleavage parallel to (001) along the fibers, giving B_2-sections. The fibres have positive elongation and show parallel extinction.

RINK analyzed the mineral and gave two possible formulae: $6CaSiO_2 \cdot H_2O$ and $8CaO \cdot 9SiO_2$. A later analysis of the mineral was carried out by C. CHRISTENSEN and showed the following composition:

SiO_2 . . . . 50.34 wt. $^0/_0$
Fe_2O_3 . . . . 0.19
CaO 47.13
H_2O 2.78

Total 100.44

The formula of xonotlite is normally given as $Ca_3(Si_3O_9) \cdot H_2O$. Recalculation of the analysis on the basis of this formula gives:

$$Ca_{3.1}(Si_{3.1}O_{9.3}) \cdot 0.7\,H_2O$$
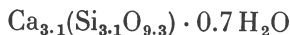
Pectolite

Samples containing pectolite gathered by Rink have been investigated by Bøggild (1953). In cavities in one of the samples, Bøggild found pectolite crystals with a maximum length of 2 mm. They were elongated parallel to the b-axis and showed the following forms: (100), (001), ($\bar{1}$01), ($\bar{2}$01), ($\bar{1}$04), (340) and (140).

In general, however, pectolite is fibrous. This is typical for the pectolite gathered both by Rink and by others on later occasions.

Pectolite, as analyzed by C. Christensen, has the following composition:

SiO_2 . . . . 54.32 wt. $^0/_0$
Fe_2O_3 . . . . 0.11
CaO 34.000
Na_2O 9.32
H_2O 2.55

Total 100.30

This analysis is in full agreement with the formula for pectolite, which according to Buerger (1957) is $Ca_2NaHSi_3O_9$.

Natrolite

Natrolite is grey-white in colour and transparent. It is optically positive with a $2V = 62° \pm 2°$. The mineral is prismatic (110) with a maximum length of 3 cm and a width of a few mm. It is often developed as penetration twins with (110) as the composition plane (Plate I, fig. 2). The cleavage is parallel to (110).

Prehnite

Prehnite was found at locations 5 and 6, fig. 3. It is fine grained, granular or sometimes bladed. The refractive indices of the mineral from

location 5 are as follows: $n_y = 1.615 \pm 0.001$, and $n_z = 1.622 \pm 0.001$. According to Tröger (1959), prehnite with these values should have an Fe^{+++} content of 3 mol. $^o/_o$, compared with the maximum possible content of 20 mol. $^o/_o$. This small amount of Fe^{+++}, if present at all, agrees with the lack of colour in the mineral.

Apophyllite

Two occurences of apophyllite were found:

a. Apophyllite from location 5, fig. 3 is fine grained, translucent and occasionally faintly bluish in colour. Optically, the variety is uniaxial negative with $n_e = 1.535 \pm 0.001$ and $n_0 = 1.547 \pm 0.001$.

b. Apophyllite from location 6, fig. 3 is developed as cubes up to 5 mm across. The mineral is dull white and weakly anisotropic, with anomalous blue to red inteference colours; $n_0 = 1.542 \pm 0.002$.

Gyrolite

Gyrolite was only found in one of the samples gathered by Rink. The mineral is scaly, with scales up to 5 mm across, and has basal cleavage. Optically it is uniaxial negative with $n_0 = 1.548 \pm 0.010$.

Gyrolite from Niaqornat, developed as hexagonal tablets, was described by Bøggild (1908), who gives the chemical composition as $2CaO \cdot 3SiO_2 \cdot 3H_2O$.

Calcite

Calcite is fine to coarse grained.

Montmorillonite

Montmorillonite is mostly developed as a very fine grained, greenish cover on the samples. It was identified by X-ray diffraction pattern.

The mineral is not genetically related to the three mineral suites, but is probably post-glacial in age, developed during alteration of the basalts.

Description of the three mineral suites

The xonotlite suite

This suite consists of xonotlite together with minor calcite and an insignificant amount of montmorillonite.

The individual xonotlite fibres are very thin and elongated. They rarely split up into single fibres but are bundled together in long stalks. This results in a ribbed surface on the samples (Plate I, fig. 1b). The fibres are occasionally woven together in dense masses. Gradual transitions from dense to fibrous xonotlite are common. Where groups of fibres are

developed, the fibres in any individual group are parallel, but there is no preferred orientation of fibres between each group (Plate I, fig. 1a).

Stalks composed of many fibres may be bow-shaped. (Plate I, fig. 1b). Only occassionally are xonotlite fibres developed in rosettes.

Many samples are cut by thin irregular fracture veins up to 3 mm wide with fibres of xonotlite interspersed with a very minor amount of fine grained calcite. The xonotlite fibres are coarse, transparent and are oriented almost perpendicular to the vein margins.

Calcite is usually developed in aggregates up to several cm across with sharp borders against the xonotlite. However, single grains enclosed in xonotlite are common. The presence of calcite does not influence the texture of the xonotlite.

Montmorillonite is usually developed as a thin cover on the samples, or is finely disseminated throughout, resulting in a greenish lustre. It may also be developed in aggregates up to a few mm across, enclosed in xonotlite material.

The pectolite suite

This suite includes the following minerals and mineral associations: pectolite, pectolite-apophyllite, pectolite-prehnite and pectolite-gyrolite. Pectolite is by far the dominant mineral. Calcite may be present with any of these minerals. Montmorillonite is also present in most of the samples.

Fibrous pectolite is white in colour and the fibres usually form rosettes up to 1 cm in diameter. A gradual transition from this type of fibres into fibres woven together in a dense mass is common.

Individual pectolite samples are developed either as structureless aggregates of rosettes or they are composed of one or several layers of dense pectolite. Sometimes two pectolite layers join together forming a double layer. These can adjoin other double layers, with a border zone rich in montmorillonite. Rarely aggregates of montmorillonite are conformably enclosed between two double layers. The samples split easily along these zones.

A few pectolite samples are cut by thin irregular fracture veins up to 3 mm wide, composed of fibrous pectolite. The pectolite fibres are more or less perpendicular to the margins. They are coarse and not particularly transparent.

Prehnite and apophyllite are enclosed in the fibrous pectolite as fine grained material. In a single sample, prehnite is formed as rosettes with diameters up to 5 mm.

Gyrolite is present together with pectolite and calcite as scales in radiating aggregates.

Calcite is developed in aggregates and as single grains similar to the calcite in the xonotlite suite.

The natrolite suite

This suite comprises the following minerals and mineral associations: natrolite, natrolite-apophyllite, natrolite-pectolite and natrolite-prehnite. Natrolite is by far the most common mineral. Calcite may be associated with all these minerals. Montmorillonite is nearly always present.

Crystals of stalky natrolite are generally grown together into a dense mass. The individual stalks are more or less parallel and it is difficult to distinguish between them. The stalky natrolite sometimes grades into a granular, fine to medium grained variety. When the natrolite stalks are not parallel, many small cavities are usually present.

A few natrolite samples are cut by fracture veins up to 1 cm in width containing stalky natrolite and calcite.

Calcite is present in abundance. It is generally grown together in fairly large aggregates enclosed in masses of stalky natrolite, without influencing the texture of the natrolite. Regularly developed natrolite stalks penetrate the calcite in all directions (Plate I, fig. 2).

The apophyllite is developed as isolated grains in natrolite material. It is only present in a few samples.

The fibrous pectolite forms rosettes with a diameter rarely greater than $1/2$ cm. The rosettes are grown together in aggregates, enclosed in stalky masses of natrolite without influencing the texture of the natrolite. Regularly developed natrolite stalks penetrate the pectolite aggregates in all directions.

Prehnite is only found in a few samples where, however, it is the dominant mineral. Macroscopically, the prehnite is dense and very fine grained; under the microscope it is seen that the prehnite sometimes forms rosettes.

The prehnite material is penetrated by stalks of fine grained prehnite (Plate I, fig. 3). These stalks are shaped similarly to the natrolite stalks which penetrate aggregates of pectolite and calcite. (Compare fig. 2 with fig. 3 in plate I). The individual prehnite grains of the stalks are larger than the grains in the prehnite mass which encloses the stalks. The prehnite grains are developed as small scales oriented more or less perpendicular to the borders of the stalks.

In one sample, cavities contain similar prehnite stalks. In another sample composed of fine grained prehnite, a cavity contains natrolite stalks. These stalks gradually change into fine grained prehnite.

The conclusion drawn is that prehnite has replaced natrolite and that the stalky aggregates composed of prehnite are pseudomorphous after natrolite stalks.

Relationship of fracture veins to host rock

The structure of some pectolite veins, composed of double layers adjacent to each other, indicates the successive and repetitive opening of the fractures. After opening of a fracture and formation of a double layer renewed fracturing took place along the contact zone between basalt and double layer, and another double layer was deposited. In a few samples aggregates of montmorillonite present between two double layers may represent original basalt fragments which became enclosed between the double layers during the repetitive opening of the fractures.

The presence of fine fracture veins with xonotlite, pectolite, calcite, and natrolite, cutting samples composed of similar minerals, also indicates that fracturing and the formation of vein material took place simultaneously.

Well developed slickenside surfaces on some vein material is proof of subsequent movement after formation of the veins.

The fracturing thus took place intermittently over a certain period of time. Simultaneously, the fractures were filled with zeolites and calc-silicate minerals.

The T-P conditions under which the mineral suites were formed

Knowledge of the geological environment in which the three mineral suites were formed, and knowledge of the stability fields of several of the minerals makes it possible to draw certain conclusions regarding the conditions under which the mineral suites were formed.

The maximum thickness of the West Greenland volcanics on Nûgssuaq is estimated to about 4 km. The formation of the vein material took place in open fractures percolated by hydrothermal solutions. The pressure of formation therefore was probably equal to the hydrostatic pressure which could have had a maximum value of 300 bars.

Knowledge of the stability conditions of several of the vein minerals makes it possible, within narrow limits, to determine the temperature of formation. According to ASSARSSON (1957, 1958) (fig. 4) and BUCKNER, ROY and ROY (1960) (fig. 5) the lower temperature limit of xonotlite formation at low water pressure is between 160°C and 280°C, and the upper limit is around 400°C. As indicated in fig. 4, gyrolite is stable above 150°C at low water pressure. According to THILO and FUNK (1950) pectolite is stable between 200°C and 400°C at low water pressure. It has not been possible to synthesize natrolite. An investigation of this mineral carried out by SAND, ROY and OSBORNE (1957) has shown that it is stable up to 290°C at water pressures from 5000–30000 lb/in^2 (550
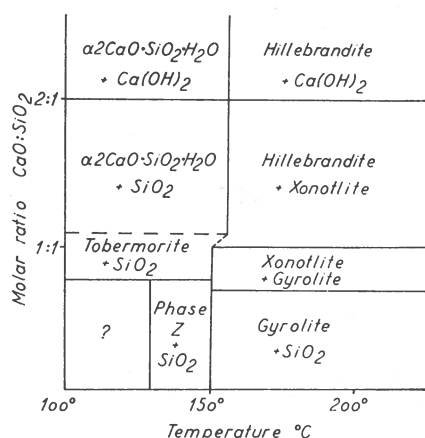
Fig. 4. Stability diagram of xonotlite and other phases at low P_{H_2O} (after Assarsson, 1958).

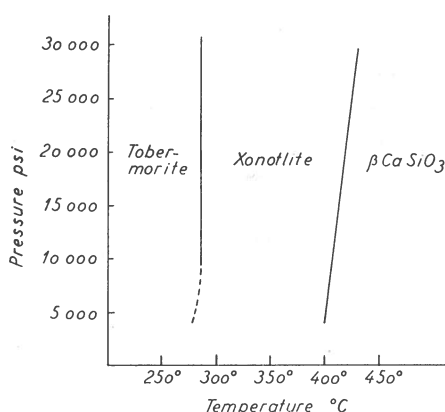Fig. 5. Stability diagram of xonotlite and other phases. Molar rotion CaO:SiO$_2$ = 1:1. (After Buckner, Roy and Roy, 1960).

bars–2000 bars). According to Fyfe and Turner (1958), prehnite is stable at temperatures from 300°C to 350°C at water pressures above 2500 bars. These writers do not exclude the possibility that the mineral is also stable at lower pressures, but then, however, the temperature range would be very narrow.

On the basis of the stability relations referred to above, the temperature of formation of the vein material in the volcanics would be close to 300°C.

Origin of the mineral-forming solutions

The formation of the vein material thus took place in hydrothermal solutions at a temperature close to 300°C and at low water pressure. Such solutions are generally considered to be of magmatic origin. They can either have originated from the host rock or have been derived from a deep-seated volcanic source. According to Coombs and Lauder (1960), fracture veins with xonotlite found in basalt in New Zealand are formed by such solutions.

The mineral-forming solutions in the volcanics at Nûgssuaq may be of similar origin. The stratigraphic position of the fracture veins in the submarine series and the overlying olivine basalts indicates that percolating sea water could have played a part in the formation of the solutions. The sea water could either have been enclosed in the basalts during extrusion on the sea bottom or have percolated down through fractures in the volcanics after their solidification but before they had completely cooled down.

The estimated chemical composition of the three mineral suites and their stratigraphic position is presented diagrammatically in fig. 6. As mentioned above, the xonotlite suite formed at the lowest levels in the volcanic formation, followed by the pectolite suite and then uppermost, by the natrolite suite. Consequently Ca minerals were deposited at the lowest levels followed by Ca-Na-bearing minerals and then by Ca-Na-Al-bearing minerals. This distribution of elements no doubt reflects a decreasing temperature of the mineral-forming solutions.

Mineral suites	Estimated chemical composition of the mineral suites						Stratigraphy
Natrolite suite							Olivine basalt
Pectolite suite							– – – ? – – –
Xonotlite suite							Tuff and pillow lava
Components	Ca	Na	Al	K	Si	CO$_2$	

Fig. 6. Diagram showing the relationship between estimated chemical composition of the three mineral suites and their stratigraphical position in the volcanic formations of the Marrait area.

Discussion

The zeolite facies is expanded by COOMBS and ELLIS (*in* COOMBS *et al.*, 1959) to include not only metamorphic rocks but also mineral associations formed under hydrothermal conditions in fractures and cavities in solid rock. (In this connection COOMBS and ELLIS do not consider the facies as a metamorphic facies but as a mineral facies).

Earlier, ESKOLA (1939) had the same idea, but rejected it, concluding that mineral suites formed under such conditions could not represent systems in equilibrium. COOMBS and ELLIS are of the opposite opinion because identical mineral suites are found in very diverse surroundings and are often of different age. However, it is stated that low temperature conditions can result in the formation of meta-stable mineral groups.

Disregarding the association prehnite-natrolite, the remaining mineral associations in the fracture veins from Nûgssuaq are considered to have formed under equilibrium conditions. Following the idea of COOMBS *et al.* (1959) the designation mineral facies condition will be used

instead of temperature condition, thus indicating that the suites formed in systems at equilibrium.

The pectolite and xonotlite suites could have been formed under the same mineral facies conditions; however, the natrolite suite undoubtedly formed under lower conditions. This assumption is based on the stratigraphic position of the suites, on the relationship between pectolite and prehnite, and on the investigation of the stability fields of these two minerals.

From the relationship between prehnite and natrolite, it can be seen that the prehnite has replaced natrolite (Plate I, fig. 3). Investagations have shown that natrolite is stable up to 290°C (SAND, ROY and OSBORNE, 1957), whereas prehnite is stable from 300°C to 350°C (FYFE and TURNER, 1958). Since these two minerals were not formed in equilibrium with each other and since prehnite crystallized in equilibrium with pectolite, the pectolite suite was probably formed under higher mineral facies conditions than the natrolite suite.

This agrees with the stratigraphic position of the mineral sequences. Natrolite is present at higher levels in the volcanic formation than pectolite. The presence of prehnite, replacing natrolite in the natrolite suite, may have resulted from a high temperature surge in the mineral-forming solutions.

COOMBS (in COOMBS et al., 1959) has described a zone in New Zealand containing metamorphically transformed rocks, where prehnite is the characteristic mineral. Stratigraphically, the zone is situated above rocks of the greenschist facies but below those of the zeolite facies. On the basis of the mineralogy of this zone, COOMBS introduced a metamorphic subfacies within the greenschist facies (or possibly a new facies) with prehnite as the characteristic mineral. This facies should be stable at 300°C ± 50° in areas where water pressure is equal to rock pressure.

It is possible that the pectolite suite, and probably also the xonotlite suite, were formed under conditions which in respect to temperature were equivalent to the facies characterized by prehnite. The two suites were therefore formed in mineral facies which lie above the actual zeolite facies. This assumption is verified by the following:

a) No zeolite minerals were formed within either the xonotlite or pectolite suites.

b) According to BUERGER (1957) and BUCKNER, ROY and ROY (1960), the water in xonotlite and pectolite is structurally different to that in a zeolite.

Consequently the following minerals and mineral associations are stable under the mineral facies conditions outlined above:

$$
\left.\begin{array}{l}
\text{Xonotlite} \\
\text{Pectolite} \\
\text{Pectolite - prehnite} \\
\text{Pectolite - apophyllite} \\
\text{Pectolite - gyrolite}
\end{array}\right\} \pm \text{calcite}
$$

The natrolite suite is presumed to have formed under mineral facies conditions corresponding to the upper range of the zeolite facies. The following minerals and mineral associations should therefore be stable under these conditions:

$$
\left.\begin{array}{l}
\text{Natrolite} \\
\text{Natrolite - apophyllite} \\
\text{Natrolite - pectolite}
\end{array}\right\} \pm \text{calcite}
$$

It appears that pectolite and apophyllite are stable in both mineral facies. This agrees with the stability range of pectolite which is between 200°C and 400°C (THILO and FUNK, 1950). In spite of the conditions mentioned in (a) above, pectolite can be found in equilibrium with a zeolite. The temperature range of xonotlite shows that it, too, is probably stable in both mineral facies.

WALKER (1960, 1961) has investigated amygdule zeolites in basalts from Iceland and Ireland. He has shown that the minerals are grouped in suites, each characterized by a few dominant minerals. The suites extend as zones through the basalts, independent of the stratigraphy of the latter. WALKER assumes that the formation of the zones is caused by differences in temperature of the mineral-forming solutions.

Within the olivine-bearing Antrim basalts in Ireland, WALKER distinguishes five mineral zones. The two most prominent contain stilbite-heulandite and analcime-natrolite as dominant minerals. The analcime-natrolite zone underlies the stilbite-heulandite zone and was therefore probably formed under higher mineral facies conditions.

The zoning within the Marrait area of Nûgssuaq is also presumed to have taken place as a consequence of temperature differences in the mineral-forming solutions. The natrolite suite probably formed at mineral facies conditions equivalent to those under which the analcime-natrolite zone in the Antrim basalts formed. The analcime-natrolite zone possibly represents the highest mineral facies conditions which have been observed in the Antrim basalts, while the natrolite suite of the Marrait area represents the lowest conditions.

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a   b

Fig. 1. a) Fibrous xonotlite sample with the fibres arranged in groups. The fibres
within each group are oriented parellel to each other but are not parallel from group
to group. b) Xonotlite specimen with strongly bowed fibres, arranged in stalks, which
result in a distinctly ribbed surface appearance.
(Photo by C. HALKIER of samples gathered by H. RINK during middle of last century).

Fig. 2. + N. 50 ×. Natrolite prisms with
penetration twins cutting through calcite
in all directions. (Photo O. JØRGENSEN).

Fig. 3. + N. 130 ×. Fine grained prehnite
penetrated by stalks of prehnite. Prehnite
of the stalks is coarser grained than the
prehnite in the surrounding mass. Prehnite
which forms the single stalks is assumed to
be pseudomorphous after natrolite. (Photo
O. JØRGENSEN)