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AND ITS COPPER MINERALIZATION AT JOSVAMINEN

BY

W. T. HARRY AND OEN ING SOEN

WITH 19 FIGURES IN THE TEXT
3 TABLES AND 3 PLATES

Reprinted from
Meddelelser om Grønland, Bd. 179, Nr. 1

KØBENHAVN
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Abstract.

The pre-Cambrian basement of Alângorssuaq, S. Greenland, comprises two main units, the Green Schists and Julianehåb Granite. The first unit, a series of sediments and basic lavas, including pillow lavas, folded and regionally metamorphosed during the Ketilidian orogeny, has been invaded and locally migmatized by the Julianehåb Granite. The last is chiefly a pink even-grained quartz – microcline – oligoclase – biotite – hornblende – rock passing into a darker less quartzose basified phase containing prominent felspars. A later medium-grained leucocratic variety also occurs. Numerous thin dykes intruding the normal and the basified granite were recrystallized together with their country rocks during moderate regional metamorphism and some have been attacked by remobilized granite. Many chiefly basic dykes of later (Gardar) age cut the basement.

Metasomatism occurs at various places throughout the area, its most striking effects in granite being desilication and formation of albite, often with chess-board structure due to replacement of microcline during deformation. Other products include garnet (apparently rich in grossularite) diopside and haematite.

Pneumatolytic-hydrothermal topomineralic reaction deposits in Green Schists at Josvaminen formed at an estimated depth of 1—3 km over temperatures between 600° and less than 100° C.

Mineralization commenced with felspathization of Ketilidian granitic rocks. To this phase some, if not all, of the syenitization of Julianehåb Granite elsewhere in Alângorssuaq may be assigned.

After an interval of time, which might have been considerable, fracturing ensued. In the schists the resultant fissures became filled by fluids from which garnet, scapolite, prehnite, diopside, actinolite and calcite were precipitated under high fluid pressures and osmotic conditions. Temperature and pressure gradients falling outwards from the voids controlled a fissure-metasomatism involving migration of lime towards the voids around which pronounced epidotization resulted. These reactions ceased and felspathization resumed locally when fluid pressures or partial water vapour pressure became unfavourable for epidotization, or lime was exhausted in the fluids.

Abstraction of other elements by silicates during felspathization and epidotization concentrated Cu and other metals in the later stage fluids, and copper ores were deposited along faults under rapidly falling temperatures and pressures, the paragenetic sequence epidote-haematite-bornite-chalcocite being explained by the topomineralic effects of the wall-rocks. Epidotization of chlorite-schists consumed much of the iron and, perhaps, by liberation of hydroxyl groups increased oxygen partial pressures with resultant crystallization of haematite and further consumption of iron; so only relatively iron-poor bornite and chalcocite could form subsequently.

Supergene enrichment is insignificant.

The mineralizing fluids were characterized by a high alkali and volatile content, low silica, Ca, Mg, Fe, Al content and a high ratio Fe/Ca. They may be connected with alkaline Gardar igneous intrusions, in particular the Nunarssuit complex which lies close at hand. However, most of the Ca, Mg, Fe, Si, Al and Cu in the minerals they produced was derived from the country rocks, and earlier phases of copper concentration may have taken place.

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Fig. 1. View W.N.W. from Naujat qâqât, Alángorssuaq. On the horizon lies Sánerut, in front of which a belt of sea-mist marks Kobberminebugt. The ridge seen immediately in front of Kobberminebugt is Julianehåb Granite of N. Alángorssuaq, cut by basic dykes. In the left foreground a little of the Julianehåb Granite on Naujat qâqât is seen, traversed by basic dykes. The Nunarssuit complex forms the low lake country (gabbro) and the rising ground on the left (Helene Granite). G.G.U. Photo. W.T.H.

I. INTRODUCTION

(a) Area described and scope of study.

Alángorssuaq, an uninhabited area about 40 km south of the cryolite mining community of Ivigtut, owes its Greenlandic name to the dark aspect of its slopes facing north to the Kobberminebugt, a place notorious for mist and bad weather. At high tide it becomes an island about 20 km long separated from the mainland to the east by Nyboes Kanal, a narrow waterway barely adequate to permit the passage of small coastal craft.

Geologically the area is divided into two; a southern portion occupied by part of the Nunarssuit complex of pre-Cambrian (Gardar) age (Harry and Pulvertaft 1963), and a northern sector composed of the pre-Cambrian basement intruded by that complex. The present paper concerns the Alángorssuaq basement and the copper deposits which it contains at Josvaminen on the Kobberminebugt. To under-

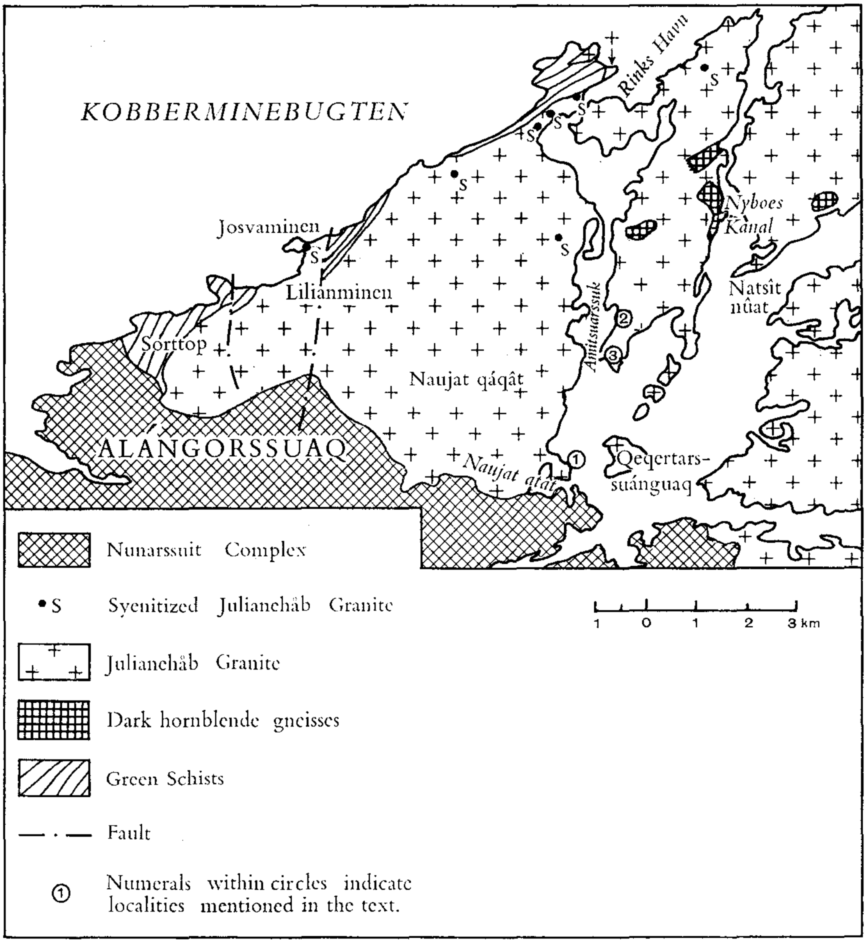


Fig. 2. Geological sketch map of Alángorssuaq.

stand the mineralization some knowledge of the basement beyond the immediate surroundings of Josvaminen is essential. Accordingly a fairly large area has been studied (see figs. 1 and 2). The first author is responsible for this and for the account of the geology of Josvaminen. The second author is responsible for the detailed descriptions (in Sect. VI) of ore minerals at Josvaminen, parts of Sect. V, and, together with the first author, the discussion in Sections VII and VIII.

In the following pages numbers quoted in brackets e.g. (39593) refer to rock samples stored in G.G.U. collections, Copenhagen.

(b) Mining history.

In the summer of 1852 the Greenlander Josva found the copper ore body now named after him on the shores of Kobberminebugt. His discovery was almost immediately investigated by the geologist Rink who reported unfavourably on its economic possibilities (Rink 1857, p. 133) but the Aalborg merchant J. H. Lundt and his English associates commenced operations and the following year a group of miners under A. Robinson, an Englishman, arrived at the mine. Twenty tons of bornite and chalcocite were soon extracted. The miners stayed over the winter and won an additional thirty tons of ore but with this the visible ore was exhausted and during the succeeding winter only two men remained at the working which by then was known as the Wheal Julia mine. Further difficulties followed when supply ships were lost at sea and in 1855 the mine was abandoned together with a good deal of extracted ore.

From 1905 to 1914 the mine was again operative under Grønlandsk Minedrift A/S through the initiative of firstly J. Bernburg and later M. Nyeboe. Houses, pumping- and power-installations were constructed shortly after the resumption of activity and though these were burnt down work was not discouraged. An inclined shaft 88 m deep on the vein, about 490 m of drifts and cross-cuts, and about 110 m of shafts and drifts in adjacent schists were cut. A new mine, the Lilianmine, was opened about $1^1/_2$ km south-west of the main Josva lode, presumably on the continuation of the latter. However, Rink's early assessment of the economic possibilities proved correct. Total production did not exceed 90 tons of copper with some small additional quantities of gold and silver. Today the mine has long been derelict and the workings are filled with water.

(c) History of general geological investigation.

The Josva peninsula was visited in 1908 by the great pioneer of South Greenland geology, N.V. Ussing, during his extensive travels in the region. His unpublished diary describes the numerous amphibolite blocks in the granite of the north-eastern part of the peninsula which he interpreted as an eruptive breccia.

Ball (1923 pp. 31—33) in a brief but useful account of the mineralogy of Josvaminen refers the copper mineralization to hot magmatic waters possibly derived from "soda-syenite magma".

Wegmann (1938 pp. 26, 27) assigned the Green Schists of northern Alángorssuaq to the Arsuk volcanic group and noted their metamorphic state, the presence of pillow lavas, the Julianehåb Granite-Green

Schist migmatites (op. cit. p. 35) and numerous generations of basic dykes. He ascribed the copper mineralization at Josvaminen to solutions from "younger granites" partially fixed by transformed pillow lavas.

Grønlands Geologiske Undersøgelse has recently undertaken the detailed geological survey of South Greenland and as part of this programme Alángorssuaq was investigated by the first author: two summer seasons, each of about three months duration were spent in the field in 1957 and 1958, and from July 29th to August 10th 1958 a special geological study was made of the Josva locality which had also been recently visited by BERTHELSEN (1958). From September 21st to 29th 1959 the locality was examined by the second author in order to study its detailed ore mineralogy.

(d) The regional chronology.

USSING's great work on South Greenland has been amplified by WEGMANN (1938) and further developed by the current field programme of the Geological Survey of Greenland (G.G.U.) so that today the complex pre-Cambrian history of the region is fairly well understood. Two major cycles can be distinguished, the Ketilidian and Gardar. During the first, metasediments and volcanic rocks were deposited. This supracrustal series was folded in the various phases of the complicated Ketilidian orogeny which was concluded by the emplacement of late- to post-kinematic granites. The consolidated Ketilidian orogenic belt was subsequently intruded by regional swarms of basic dykes that have in places been later deformed and metamorphosed in the Sanerutian period (BERTHELSEN 1961 p. 333) marked by recrystallization and reactivation of the Ketilidian "Julianehåb Granite".

After a long period of erosion the Gardar cycle was initiated and a supracrustal succession of lavas and sandstones, now preserved by faulting in the Igaliko region, was laid down on the granites. Numerous generations of dykes were intruded, important faulting took place, and the plutons of the South Greenland alkaline province, of which the Nunarssuit complex is an important member, were emplaced.

Finally a swarm of roughly N.W.-trending dolerite and olivine-dolerite dykes, tentatively assigned to the Tertiary, invaded the region.

(e) Acknowledgements.

The writers are indebted to mag. scient. K. ELLITSGAARD-RASMUSSEN, director of Grønlands Geologiske Undersøgelse, for permission to publish this account and invaluable encouragement, to Prof. A. BER-

THELSEN for useful discussion and access to unpublished information concerning the distribution of mineralization in S. Greenland, and to Skipper H. VALENTIN for willingly arranging field transport. Thanks also are due to stud. mags. L. HØJAAS, E. SCHOU JENSEN, E. KANNEWORFF, S. ØDUM, and M. GHISLER who provided assistance in the field. In addition Mr. SCHOU JENSEN voluntarily gave welcome and efficient assistance in mapping the dykes of the region. The text figure drawings were prepared at the G.G.U. drawing office in Copenhagen.

The first author is particularly indebted to the Court of St. Andrews University, for leave to pursue his studies in Greenland, and to Professor C. F. DAVIDSON for the benefit of discussion.

II. THE GREEN SCHISTS AND JULIANEHÅB GRANITE

(a) The Green Schists of N. Alángorssuaq.

(i) General remarks.

An impersistent strip of Green Schist belonging to the Ketilidian supracrustal cycle runs north-eastwards along the northern shores of Alángorssuaq (fig. 2) and comprises a variety of rocks in plane parallel layers up to several metres thick, striking more or less along the coast and either vertical or steeply inclined to the south-east. This lithological layering is roughly concordant with schistosity, cleavage, and the axial planes of minor folds, some of which are demonstrably shear folds. Examples of the last seen about 100 m west of Lilianminen are a few cm in amplitude and have axes plunging E.N.E. at 20—30 degrees.

Also roughly concordant with the lithological layering are several shear zones marked by the development of gray fine-grained mylonitic schists. One such zone 100 m wide, about 5 km N.E. of Josvaminen, involves both Julianehåb Granite and Green Schist. The foliation planes within it strike N. 50 E. and dip S.E. 60—70° parallel to the Green Schist—Julianehåb Granite contact. Another mylonitic zone occurs in the footwall of the Josva vein.

The most distinctive rock types in the Green Schists of N. Alángorssuaq are described briefly below. Mylonitic schists of felsitic aspect will be dealt with in Section II (e).

(ii) Plagioclase porphyrites.

Rocks not unlike the plagioclase porphyrites described by Sederholm (1923) from the Pellinge district of Finland, though with less thinly tabular felspars, are best developed towards the north-eastern extremity of the coastal strip. In hand-specimen they are fairly pale gray rocks with abundant rectangular felspars up to a few cm long in a fine-grained often epidotic matrix. The felspars tend to lie parallel to the margin of the porphyrite in which they occur and sometimes are highly deformed. The porphyrite layers are generally concordant with the foliation of the adjacent schists but sometimes they transect the latter at a small angle. Occasionally the boundaries of the layers are thrown into minor folds with axial planes subparallel to the schistosity of the surrounding rocks; the porphyrites involved in this folding contain highly deformed felspars some of which have been twisted into "boomerang" shapes without having been shattered.

In thin-section under the microscope the plagioclase porphyrites containing bent felspars have obviously been highly recrystallized during deformation. Their felspar phenocrysts are andesine showing albite and pericline twinning and partly recrystallized to granular aggregates of clear andesine enclosing stumpy epidote crystals apparently formed in equilibrium with their host. The unrecrystallized parts of the phenocrysts are saussuritized. Thin veinlets of microcline occasionally penetrate the phenocrysts and equant microcline crystals may occur as components of the granular recrystallized felspar. The groundmass of the rock is a granoblastic aggregate of abundant equant andesine and subordinate well-twinned microcline crystals together with green hornblende and brown biotite showing a pronounced preferred orientation along planes flowing around the plagioclase phenocrysts. The hornblende, which also forms sporadic porphyroblasts, is pleochroic from a pale brownish-green to a deep-green colour with slight blue tint.

(iii) Uralite porphyrites.

Dark green schists composed largely of green hornblende forming both part of the groundmass and larger crystals or crystal aggregates a few mm long occur sporadically. Sometimes they bear elongated vesicles up to 5 cm long lined with epidote and containing magnetite or haematite. In many respects they recall the uralite porphyrites of SEDERHOLM (1923). Good examples of them bearing large amphiboles 1 cm long (39591) are seen near the Nunarssuit complex, close to the S.W. extremity of the coastal Green Schist belt.

(iv) Pillow lavas.

Pillow structures were noted by WEGMANN (1938) in the deformed metamorphosed lava in the hanging wall of the Josva vein but are difficult to discern. The rock concerned (39550) is composed almost wholly of amphibole (Z = bluish green) whose tendency to parallelism imparts a crude schistosity; thin calcite lenticles and occasional pistacite grains are present. More readily recognizable pillow structures are visible on the coast 1200 m E.N.E. of Josvaminen and about 1800 m W.S.W. of Lilianminen. At the last locality the pillows (39593) are light-gray irregular oval bodies 15—30 cm long in a darker matrix; their shape suggests a "younging" to the south-east. The pillow lavas E.N.E. of

Josvaminen include a flow 6 m thick with lenticular vesicles and elongate pillows (39501) which are 10—30 cm long, about one-sixth as broad, and are set in darker schist.

(v) Banded schists.

In addition to the well-defined varieties just noted the Green Schist belt includes a number of medium- to fine-grained gray or green banded schists containing different proportions of quartz, microcline, plagioclase, brown biotite, green hornblende, pistacite, and accessory sphene, apatite, ore. Some layers are rich in epidote, others contain abundant biotite or hornblende, and some are fine-grained gray quartzo-felspathic rocks.

(vi) Epidote balls and lenses.

Epidote balls and lenses up to a metre long are common within the plagioclase porphyrites and other rocks throughout the Green Schist outcrop. In thin-section they are seen to be fine-grained granular aggregates of pistacite (39439) with a little quartz often concentrated in veinlets. In some outcrops the epidote masses are common in plagioclase porphyrites but are absent in the adjacent hornblende schists. Fine-grained concentrations of granular pistacite in concordant or cross-cutting veinlets are also frequent in the Green Schists. Some of these are related to the copper mineralization at Josvaminen as will be discussed later.

(b) Green Schists within the Julianehåb Granite outcrop.

Small outcrops of Green Schist occur at a few places throughout the Julianehåb Granite outcrop in Alángorssuaq. On the promontory west of Qeqertarssuánguaq a strip of schists a few metres wide is migmatized by the Julianehåb Granite at its borders. The schists are banded and include layers of a green rock largely composed of a bleached decussate pale green amphibole ($Z \wedge c = 22°$, Z = pale green, X = almost colourless or very pale brown) partly replaced by some ragged areas of brown biotite with a slight reddish tint. Interstitial felspar occurs. Where the rock is strongly attacked by the granite it contains many small irregular clear oligoclase areas enclosing numerous decussate needles of an amphibole like that composing the main body of the rock. Felspathization seems responsible for bleaching the amphibole, and releasing iron to form abundant minute ore inclusions in the amphibole.

Near the tip of the small peninsula Natsît nûat south of Nyboes Kanal banded Green Schists striking north-south include gray thinly-foliated quartzo-felspathic schists with some thin epidote ribs, some bands of plagioclase porphyrite with felspars 2—3 mm long and layers of hornblende-felspar rock like the "dark hornblendic gneisses" described below. These hornblende-felspar layers, which contain thin concordant ribs of gray sometimes epidotic schists 1 cm or so thick, have a slightly patchy structure due to their variable felspar content. They contain occasional epidote balls 20 cm or so long, and are obviously part of the Green Schist complex. In slice they are seen to consist of abundant highly sericitized oligoclase or andesine, some areas of clear non-perthitic microcline, quartz, and plentiful green hornblende crystals up to 2 mm long locally replaced by a chlorite mineral associated with mica. The chloritization of the amphibole was accompanied by liberation of titanium, for microscopic sphene granules occur abundantly in the chlorite. Sphene also forms larger spongy crystals 1—2 mm long. Other accessories are epidote and apatite; iron ore is virtually absent. A few hundred metres to the east the hornblendic gneiss passes locally into a rock consisting of a very pale optically negative green amphibole within, and at the expense of which, hornblende porphyroblasts have grown. This rock is veined by the Julianehåb Granite.

(c) Dark hornblendic gneisses.

Roughly oval or boss-like more or less uniform outcrops of dark hornblendic gneiss up to several hundred metres across occur at a number of places within the Julianehåb Granite (see fig. 2). The gneiss contains abundant hornblende in crystals averaging 1—2 mm long with Z = deep green often showing a faint blue tint, X = pale brown, and $Z \wedge c = 22°$. A faint preferred orientation may be visible in the hornblende crystals. A little dark brown biotite is present in some samples (30131). Epidote, sphene and apatite (in crystals up to 1 mm long) are accessory; iron ores are not common.

Many though not all the gneisses also contain irregular interstitial felspar areas about 1—2 mm long forming up to roughly half the volume of the rock and consisting of either oligoclase or andesine both of which are often saussuritized. Such rocks may also bear twinned microcline and a little quartz in small polycrystalline patches (30141).

(d) The Julianehåb Granite.

(i) The normal granite of the area.

Most of the Alángorssuaq basement is composed of a pale pink aphyric medium- or slightly coarse-grained hypidiomorphic granite without compositional gneissic banding, well seen on and in the vicinity of Naujat qáqât. It contains the following minerals.

Quartz forms polycrystalline medium-grained areas, usually not exceeding about 0.5 cm in length, composing between one third (as in most specimens) and, exceptionally, about half the volume of the rock. Strain effects are moderate or absent and inclusions other than dust are rare.

Microcline is common in all slices examined. Together with plagioclase it sometimes shows a pronounced tendency to segregate in areas several cm wide (e.g. 30133).

The crystals are characteristically twinned, clear, unaltered, and measure up to a few mm sometimes as much as 0.5 cm across. They tend to be equant and are not interstitial though they are generally xenomorphic. Perthitic structures are virtually absent. A little myrmekite occasionally occurs at the boundaries between microcline and oligoclase, and some microcline crystals are traversed by late microveinlets of sodic plagioclase (30001).

Oligoclase is common in all slices examined. The crystals are usually equant with poor outline but can be rectangular. Many exhibit altered cores containing numerous small biotites and hornblendes and surrounded by well-defined clear plagioclase rims 0.2 mm wide free of inclusions. Most show thin albite twin lamellae and are slightly turbid with alteration. Zoning is usually absent.

Dark minerals are either present in only small quantities or sometimes absent (as in 30062). The commonest of them is biotite, brown in colour with a faint olive tint, 2V nearly 0°, forming flakes up to 1 or 2 mm long but frequently only 0.1 mm in length, occasionally containing microscopic zircon inclusions surrounded by pleochroic haloes. The small biotite flakes are commonly concentrated in small aggregates.

A little green hornblende is often also present. It forms small spongy crystals and tends to be closely associated with biotite.

Accessories. Sphene is an abundant accessory occurring both as minute colourless granules—often concentrated in small nests or forming rims round ore grains—and large spongy pink crystals 1—2 mm long of very irregular outline (30133) sometimes enclosing apatite crystals. The small sphene granules tend to be associated with biotite aggregates and are often either enclosed by biotite or concentrated at the margins of biotite flakes. The large sphenes do not tend to be associated with biotite.

Other accessories are epidote, apatite and iron ore; orthite has been seen in only one slice.

Over an extensive tract the normal Julianehåb Granite has suffered some penetrative deformation, as can well be seen in the coastal exposures running northwards from loc. 1 on fig. 2 along the western shores of Amitsuarssuk. Here it is traversed by innumerable closely-spaced anastomosing shear surfaces dipping steeply and striking between N.-S. and N.E.-S.W. Patterns indicative of sinistral movement occur (fig. 3). The surfaces are often epidotic and quartz in the granite tends to form highly flattened lenses aligned parallel to them. Some are marked by concentrations of small brown biotite and green hornblende

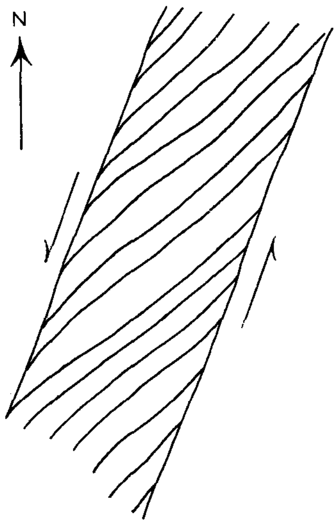


Fig. 3. Diagrammatic sketch to indicate sense of lateral displacement on closely spaced planes of transcurrent shearing and recrystallization in Julianehåb Granite, west shores of Amitsuarssuk, seen in horizontal surface. The two parallel relatively important N.N.E. movement planes bounding the pattern are about 30 cms. apart.

crystals that are aligned obliquely to (and obviously grew during the formation of) the shear surfaces. Such concentrations can pass along the shears into quartzose films offset by cross-cutting quartz films. All these structures are impartially cut without displacement by the joint system. The shearing has locally resulted in mylonites (e.g. 30034), fine-grained occasionally fluoritic quartzo-felspathic rocks with a vertical microscopic planar banding striking N.-S., and sometimes including epidotic layers.

The shears are truncated by Gardar dykes, for example the dolerite dyke that runs W.S.W. up to Naujat qáqât.

(ii) Porphyritic granite and leucocratic granite.

A variable relatively dark porphyritic granite that differs from the normal granite in bearing conspicuous felspar phenocrysts or porphyroblasts and in being richer in dark minerals and poorer in quartz is extensively developed in eastern Alángorssuaq where it contains many bodies of the dark hornblendic gneiss described above. Contacts with the normal granite can sometimes be located within a few centimetres but in northern Alángorssuaq a gradual passage appears to take place between the two types in traversing from Rinks Havn eastwards along the coast.

On an island $1^1/_2$ km south of Nyboes Kanal coarse quartzose leucocratic granite sends veins with sharp contacts into the porphyritic dark granite, and on the shore of the mainland nearby a sheet several metres wide of leucocratic even-grained medium-grained granite cuts the dark granite (39596). Similar leucocratic medium or rather fine-grained granite forms rising ground 3—4 km east of Nyboes Kanal and large outcrops about $1^1/_2$ km S.E. of that Kanal. On the east shores of Amitsuarssuk at loc. 2 the porphyritic granite (30122) is cut by a 1 metre wide sheet of medium-grained aphyric granite and further north, about 250 m north of lat. 60°52.5 agmatitic porphyritic granite lies in sharp contact with a rock (30157) which differs from the normal granite only in that microcline is the dominant felspar almost to the exclusion of oligoclase.

Under the microscope the porphyritic granite shows much the same minerals as the normal granite though distinctions exist. Microcline microperthite and twinned oligoclase form large crystals up to a few cm long, some with clear microcline rims round oligoclase cores containing numerous small epidote inclusions. In the medium- to rather fine-grained groundmass twinned microcline and oligoclase are abundant and some felspars have oligoclase cores surrounded by microcline rims. Myrmekite is common between oligoclase and microcline and is abundant in one sample (30122). The same sample also shows plagioclase partly replaced by microcline which encloses numerous optically continuous oligoclase areas with myrmekite borders. Where microcline and oligoclase individuals are in contact with each other the former often contains numerous oligoclase inclusions near its margin. Quartz is only present in moderate amount and does not show the strong tendency to be concentrated in conspicuous polycrystalline areas seen in the normal granite. Biotite and hornblende comprise the dark minerals and show the same pleochroism as the corresponding minerals in the normal granite. Zircon inclusions surrounded by pleochroic haloes occur in the biotite. Sphene is an abundant accessory as tiny colourless grains at the margins of ore minerals or associated with biotite; pink ragged sphene porphyroblasts 1—2 mm long also are present. Other accessories are epidote, ore and apatite.

(iii) Migmatites within the Julianehåb Granite outcrop.

Migmatites, chiefly agmatitic or nebulitic, occur at many places throughout and well within the outcrop of the Julianehåb Granite. They seem more common in the dark porphyritic granite than in the normal granite. Some surround and pass into small outcrops of Green Schist and dark hornblendic gneiss from which they have clearly been derived by the migmatizing action of the surrounding granite. Others show no such relationship and are simply isolated patches in the granite marked by numerous rounded or oval inclusions less than a metre long which may or may not be readily identified as partly transformed Green Schists and dark gneiss. Inclusions of doubtful origin differ from the enclosing granite solely in being slightly finer-grained and richer in dark minerals. The granitic matrix of many of the migmatites has been basified by increase in dark minerals and decrease in quartz.

A few examples will be taken to illustrate the migmatites, commencing with those not directly associated with schists or dark gneisses.

On both shores of Amitsuarssuk the normal and porphyritic granites are frequently agmatitic. The eastern shore of that inlet, about 1200 m north of loc. 2, shows dark porphyritic granite containing numerous rounded or oval inclusions less than 1 metre long that tend to lie parallel to the margin of the adjacent leucocratic granite (30157 mentioned above) that cuts them. The inclusions differ from their matrix only in being richer in dark minerals and finer-grained. When these distinctions are not marked the migmatite becomes nebulitic. The enclosing granite passes gradually into normal granite over several hundred metres north-north-eastwards. To the south-east a basified migmatitic granite is commonly seen for some distance. This is rather fine-grained (av. grain-size about 0.5 mm) and has a sutured texture. It contains only moderate amounts of quartz (in single crystals or small aggregates of two or three crystals) twinned oligoclase with turbid centres and clear rims, and microcline which though common is perhaps subordinate to oligoclase; green hornblende is common often in aggregates up to 2 mm long, sphene is an abundant accessory and iron ore is virtually absent.

Migmatites associated with schist or gneiss are numerous. On the promontory at loc. 3 (fig. 2) green hornblende-rock is veined and agmatized by a variable dark porphyritic granite which is virtually augen-gneiss and is cut by veins of more leucocratic granite. The agmatitic blocks have irregular, corroded outlines, measure from a few mm to almost a metre in length and do not exhibit reaction rims. On the west side of the same promontory, 200 m north of its southern tip, green hornblendic rock chiefly comprising green hornblende, brown biotite and some yellow pistacite, is traversed by small permeation veins consisting of microcline and oligoclase with strong reaction textures, some quartz and green hornblende, a little colourless or very pale green probably diopsidic clinopyroxene as single crystals or rims round hornblende, accessory sphene, zircon and apatite (30124, 30125). Roughly 50 m from the last locality normal granite passes into a darker rather fine-grained granitic rock containing lenticular green hornblende aggregates a few mm long arranged in parallelism, plentiful microcline of which some forms scattered small porphyroblasts, and a few vague nodules. The last are 1 cm or so across and chiefly consist of well-twinned albite sometimes with chess-board structure; chlorite in decussate sheaves and biotite are present; quartz is absent (30126).

About 100 m to the north of the last locality permeation of hornblende-rock has resulted in a gray granitic rock containing nodules 5 cm long bearing rims rich in penninitic chlorite and cores consisting of albite aggregates together with a little biotite and muscovite. As in the other nodules just mentioned signs of deformation are totally absent.

On the peninsula Natsît nûat migmatitic Julianehåb Granite containing vague darker inclusions with felspar porphyroblasts attacks schist and dark gneiss. The granite is medium-grained and rather dark. Its dominant felspar is oligoclase rimmed by clear sodic plagioclase; microcline is very common and interstitial; myrmekite based on oligoclase commonly occurs at the boundaries between the two felspars and penetrates the microcline; other reaction textures are frequently exhibited by the felspars. Quartz is relatively scanty; green hornblende and biotite are much more abundant than in the normal granite and form crystals up to 1 mm long. Epidote is common and can form euhedral inclusions in biotite. Sphene is an abundant accessory occurring as tiny colourless grains and xenomorphic pink crystals up to 2 mm long which can enclose euhedral plagioclase. Other accessories are a little apatite and ore.

Near the big dolerite dyke on the west side of the inlet south of Nyboes Kanal dark hornblendic gneisses are attacked by granite to form nebulites and agmatites. Similar phenomena are seen about 1 km west of and also 1 km S.W. of the canal.

(iv) Migmatites near the boundary between the Julianehåb Granite and Green Schists of Kobberminebugt.

Julianehåb Granite—Green Schist migmatites are common along the boundary between those two units near Kobberminebugt.

The Peninsula at Josvaminen.

A striking agmatite is well exposed in the north-eastern part of the small peninsula at Josvaminen (figs. 4—6). Here pale pink Juliane-

Fig. 4. Agmatite of Green Schist (amphibolite) in Julianehåb Granite north-east part of the peninsula at Josvaminen. The vertical hammer-shaft, top right, is 50 cm long. G.G.U. Photo. W.T.H.

håb Granite with sporadic felspars a few mm long in a variable medium- to fine-grained base contains agmatitic inclusions that are scanty in some places but elsewhere make up about half the exposed rock surface. The granite sometimes shows a vague streaky banding, especially near the inclusions. The latter vary in length from a few centimetres to several metres and are generally elongated. Their margins are distinct or vague, and are often marked by a zone rich in amphibole no more than a few mm wide, though there are no conspicuous reaction rims like those seen between mafic and granitic gneisses in certain other areas, for example the Canadian Grenville (Harry 1961, p. 5). Many of the blocks have ragged terminations interdigitating with their granitic matrix which can also form long thin vague folia within and parallel to the schistosity of the blocks, as well as cross-cutting veins.

Except for one felsitic fragment 8 m long the inclusions are either dark-green amphibole-rocks like many in the Ketilidian Green Schist outcrops of the region, or amphibolitic to dioritic rocks varying in felspar content according to the degree of permeation by the enclosing granite, which when pronounced forms nebulites.

The schistosity of the blocks (due to preferred orientation of amphibole) and the lengths of elongated blocks strike north-eastwards as does a prominent joint direction. Planes of shearing, partly healed by recrystallization and marked in thin-section by trains of fine-grained

Fig. 5. Agmatite, same general locality as fig. 4.
G.G.U. Photo. W.T.H.

Fig. 6. Partly digested amphibolite block in agmatite. Same general locality as fig. 4.
G.G.U. Photo. W.T.H.

granular quartz and felspar, run in various directions and sometimes displace the blocks slightly, giving them angular outlines. These movements are clearly later than the migmatization; so too are certain metasomatic effects, which seem connected with the copper mineralization at Josvaminen described and discussed in later sections. For the moment rocks which have suffered little or no modification by this metasomatism will be described. Modified rocks will be dealt with in Section V.

The granitic component of one agmatite specimen (39507) consists of abundant quartz and microcline perthite, accessory sphene and epidote, the last tending to cluster in small aggregates. The sphene forms numerous tiny colourless grains and pink xenoblastic crystals up to 2 mm long with thin discontinuous colourless rims: The blocks enclosed by this granite bear green amphibole in scattered crystals and aggregates (associated with biotite) up to 0.5 cm long in a fine-grained groundmass of abundant green hornblende and brown biotite crystals arranged in parallelism; some felspar, including plagioclase, occurs, and tiny disseminated epidote crystals are an abundant accessory.

A rather fine-grained partly digested agmatitic block on the west shores of Harriet's Havn (39574) largely consists of abundant xenomorphic untwinned oligoclase a little of which forms small porphyroblasts containing abundant tiny hornblende and biotite crystals. Its other components are green hornblende in fair amounts, moderate quantities of brown biotite with an olive green tint, disseminated pistacite grains of obviously primary metamorphic origin, and accessory sphene. Some of the dark minerals are concentrated in small sporadic decussate areas.

On the shore at the south-west end of the Josva peninsula normal Julianehåb Granite passes into a basified nebulitic migmatitic phase containing numerous lenticular aligned inclusions of schist and green amphibole-rock with small hornblende porphyroblasts. The basified granite (39528) is heterogeneous in hand-specimen. Its paler parts consist of small amounts of quartz, fair quantities of microcline and plagioclase together with green hornblende often intergrown with a pale green clinopyroxene. The darker portions contain little or no quartz, abundant green hornblende (Z = blue-green), some felspar, and notable amounts of pistacite in well-formed crystals. Sphene is accessory. Followed along the shore for a short distance this migmatite passes into a dioritic-looking phase opposite the island. In this (39531) oligoclase with bent twin lamellae is common and there is some quartz and microcline, though the latter is subordinate to oligoclase in quantity. Brown biotite is abundant and there is a little green hornblende (Z = bluish-green). Pink sphene, zircon and ore are accessory.

At the S.W. end of the peninsula a medium-grained leucocratic tongue intruding Green Schist consists essentially of abundant quartz and twinned (sometimes chess-board) albite. Potash felspar is scanty; it forms very irregular interstitial areas and inclusions in plagioclase which has apparently replaced it. Sphene is an abundant accessory as small granules concentrated on planes of granulation. Mortar structure is well developed in the rock.

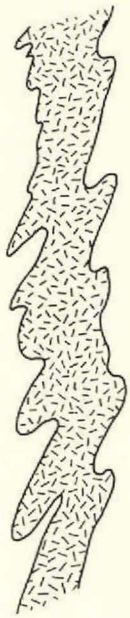


Fig. 7. Quartz felspar vein, a few cms wide, in migmatitic Julianehåb Granite, near Lilianminen. The sinuosities are due to folding on parallel axes roughly normal to the general strike of the Green Schists in the vicinity.

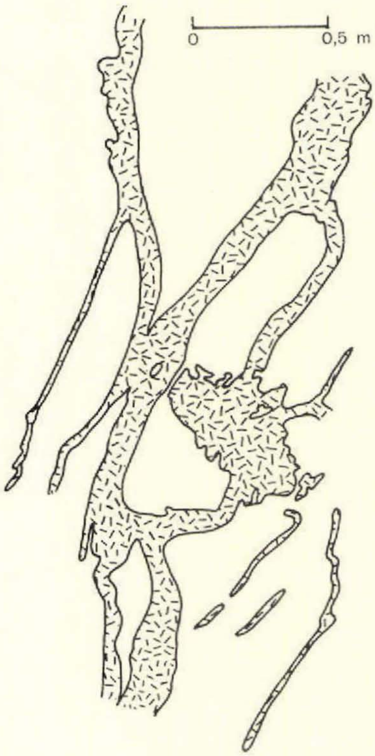


Fig. 8. Quartz-felspar veins, later than the folded veins (e.g. fig. 7) in migmatitic Julianehåb Granite near Lilianminen.

Migmatites near Lilianminen.

On the east side of the small promontory near Lilianminen the Julianehåb Granite is a gray relatively fine-grained migmatitic rock with small inclusions of biotite-hornblende schist and a fine-grained granular epidote-rock like that forming the epidote balls in the Green Schists of the district. The granite is slightly granulated and contains abundant quartz and oligoclase. The last is sometimes antiperthitic and often contains minute quartz blebs apparently released when the plagioclase replaced microcline (39553). Green hornblende and brown biotite are common; microcline is not. Epidote, sphene and a little diopsidic pyroxene are accessory.

The migmatite is traversed by numerous ramifying aplitic to pegmatitic veinlets from a few mms to tens of centimetres in thickness that can be regular or contorted (fig. 7), have sharp or vague boundaries and sometimes fade into the migmatite. Two generations are visible, one whose members intersect without offset, and a later more leucocratic

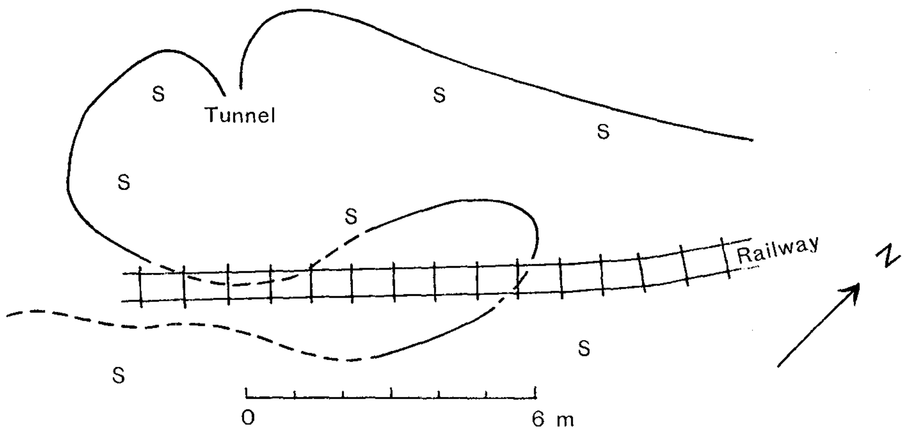


Fig. 9. Plan of the contact between dark porphyritic Julianehåb Granite and syenitized Julianehåb Granite (S) at and near the small tunnel about half-way along the railway track (indicated by parallel lines) crossing the peninsula at Josvaminen.

set of veins that cut and displace the older generation though they appear to be replacements from their form (fig. 8). A folded member of the older generation (39560) chiefly consists of granulated oligoclase crystals up to 2 mm long with bent and ruptured twin lamellae and often a patchy antiperthite structure. Quartz is common, tending to form polycrystalline areas. Potash felspar is not common. Green hornblende and greenish-brown biotite form small crystals associated with fine-grained granulated felspar and frequently enclosed by the large felspars. Ore with sphene rims is accessory.

(v) Syenitic phases within the Julianehåb Granite.

Medium- to slightly coarse-grained very pale-weathering rock, consisting almost wholly of felspar and with small disseminated haematite flakes as a conspicuous accessory, forms areas up to several hundreds of metres across in the Julianehåb Granite, especially near the Green Schists of Kobberminebugt (fig. 2).

An example is the neck of the peninsula at Josvaminen. The contact of this area with the finer-grained and darker, often porphyritic or porphyroblastic migmatitic granites to the north-west is sharp and steeply-dipping (60° S.E. at Harriet's Havn). It is not marked by cold shearing, nor does either the syenite or the granite become finer-grained towards it. In detail it can be intricate as illustrated in fig. 9. It seems to truncate dark inclusions in the syenite at Harriet's Havn and this may be due to the hot shearing common throughout the peninsula, which is marked in the syenite by numerous white-weathering anastomosing albite films trending north-east at the tunnel mentioned in the explanation of fig. 9 but from N.N.W. to N.N.E. (dip S.E. 75° and E. 80° respectively) elsewhere in the peninsula. These films can be so numerous as to impart a crude foliation to the syenite and at the S.W. limit of its outcrop, near the dyke whose relationships will be discussed later, they locally follow the margins of the dyke though in places they are cut at right angles by the dyke. In thin-section they are seen as trains of deformation and granulation of felspar.

A sample of the syenite (39514) collected near the normal granite to the south-east contains abundant perthite, dusty with alteration, in crystals from 0.5 mm to exceptionally 0.5 cm across. Clear albite, often with chess-board structure, sometimes obviously replaces, and frequently forms veinlets crossing the perthite. It is commonly deformed, exhibiting bent and broken twin lamellae. There are small amounts of a muddy-brown altered hornblende or biotite in small aggregates of minute crystals. Haematite forms films on felspar cleavage planes. Sphene and carbonate are accessory. Quartz is absent.

Another specimen (39518) from the north-west corner of the outcrop has S.G. 2.62 and shows the same phenomena. In addition it contains small crystals of pale green diopside, garnet, and zircon, the first being commonly deformed and, together with garnet, concentrated in granulated areas.

On the other hand in another sample (39516) from near 39514 albite, often with good chess-board structure, predominates and potash felspar is rather scanty. Epidote and small specular haematite flakes are accessory.

A small syenite area about 3.5 km S.W. of Rinks Havn very clearly demonstrates a gradual passage into the surrounding granite. A sample (39570) consists of abundant microcline perthite and albite (without chess-board structure), some green diopside, a fair amount of xenoblastic garnet, a little carbonate, haematite and zircon. Quartz is absent. The coloured minerals tend to form fine-grained aggregates together with fine-grained felspar (the rock is rather strongly granulated) and the garnet forms crystals up to 1 mm long enclosing granulated felspar fragments.

Another area, roughly 1.200 m S.W. of the S.W. end of Rinks Havn, consists almost wholly of microcline perthite. There is some albite (twinned but not zoned and devoid of chess-board patterns though the rock has been granulated) carbonate and haematite.

Besides these areas large enough to show on fig. 2 there are, scattered throughout Alángorssuaq, smaller areas of similar syenite within and passing into the Julianehåb Granite. A specimen (39559) from one near Lilianminen has abundant perthite, chess-board albite and a little yellow garnet. A peripheral sample (39552) from the passage to granite has a little quartz in flattened lenses corroded by felspar, abundant chess-board albite (with inclusions of more calcic plagioclase), some microcline-perthite, accessory haematite and apatite. The rock, though granulated, is on the whole medium-grained.

The sheared Julianehåb Granite well seen in coastal exposures running northwards from loc. 1 on fig. 2 along the western shores of Amitsuarssuk and described in Section II(d)(i) sometimes bears late chess-board albites a few mm long which have suffered little or no deformation and replace strongly deformed albite-oligoclase. Oligoclase forms many small inclusions in the late albites. Microcline may or may not occur. Quartz can be either absent (30031) or present in only minor amounts (30032). Some samples closely resemble the syenite at Josvaminen.

Close to loc. 1 on fig. 2 such albitized rocks contain moderate amounts of one or more of the following: garnet, diopside, epidote, biotite, green hornblende, fluorite, sphene apatite, occasional ore. Intricate reaction textures are associated with this mineralization, and original green hornblende can be attacked with liberation of finely disseminated iron oxides and formation of sphene rims round the amphibole.

(e) Felsitic rocks.

(i) Aphyric intrusions.

Aplites, pegmatites and quartz veins are not common in the Julianehåb Granite of Alángorssuaq but the Green Schists near the granite in the northern part of the area often contain felsitic rocks that may largely be altered aplitic derivatives of the Julianehåb Granite, for they increase in size and number towards the granite. Near an inlet about 1.5 km W.S.W. of Lilianminen, for example, irregular masses of pink felsite with sharp or vague contacts send discordant apophyses into the surrounding schists and also vein the Julianehåb Granite. Similar veins cut non-migmatized schists at the granite boundary roughly 1 km S.W. of Rinks Havn and a place about 1.5 km east of Josvaminen. Large discordant massive irregular felsite bodies of similar type cut the schists N. and N.E. of Sorttop.

The felsites are fine-grained (sometimes no more than 0.1 mm in av. grain size) usually massive pink rocks essentially composed of allotriomorphic albite and potash felspar in highly variable proportions. Quartz may be absent but can be abundant. Thin epidotic folia and lenses may be present and magnetite, chlorite, muscovite, epidote, sphene, apatite, garnet, actinolite, calcite are possible accessories. Some albite-rich samples, containing nests and veinlets of fairly coarse-grained albite and radiating actinolite aggregates, seem to have suffered soda metasomatism. Felsites near Sorttop bear epidote and malachite coatings on joint planes and are traversed by epidotic veinlets.

(ii) Porphyritic intrusions.

On the shores of Kobberminebugt west of Rinks Havn a 3 m wide felsite with small felspar phenocrysts aligned parallel to the length of the sheet (39440) lies concordantly in Green Schists and can be followed for several hundred metres. Near and N.E. of Josvaminen a felsite bearing idiomorphic quartz phenocrysts several mm wide lies in contact with plagioclase porphyrite.

(iii) Felsitic schists formed by mylonitization.

Fine-grained mylonitized rocks with thin pale pink and green bands occur in the footwall of the Josva vein. A typical specimen (39551) bears andesine porphyroclasts up to a few mm long broken up and dragged out along planes parallel to the banding of the rock. The albite twin lamellae of the porphyroclasts are conspicuously bent and ruptured. The groundmass of the rock (av. grain size 0.05 mm) which is largely felspar with some dark mica, amphibole, apatite, ore and sphene exhibits a pronounced microscopic foliation or mylonitic banding, due to parallelism of mica and wrapping round the andesine porphyroclasts.

Concordant with this felsitic layer are bands of chlorite-schist, chlorite-biotite-schist and epidote-amphibole-schist.

Elsewhere in the Green Schist outcrop small bands of mylonitized schists sometimes occur along shear zones striking roughly parallel to the schistosity of the surrounding rocks. Like the occurrence just described they have a felsitic appearance and were formed by shearing of Green Schists.

(iv) Felsitic schists of uncertain origin.

Some felsitic bodies with vague contacts are of uncertain origin: they may have formed by combined mylonitization, felspathization of schists, and magmatic intrusion. As will be mentioned in Section IV it is, however, most unlikely that felspathization has been the main factor in producing noteworthy bodies of felsite.

III. MINOR BASIC INTRUSIONS OF UNCERTAIN AGE AND DYKES

Numerous dykes belonging to several generations cut the Alángorssuaq basement but most of them are too small to represent on fig. 2. There are also a few minor intrusions of uncertain age that appear to be small irregular boss-like bodies.

(a) Minor basic intrusions of uncertain age.

A small gabbroic body on the shore about 1 km S.W. of Lilianminen (39595) consists of well-twinned saussuritized labradorite, pale green uralitic amphibole and brown biotite with accessory apatite. Petrographically it is not unlike many Gardar intrusions.

An altered brecciated variable basic mass (30075) on the north-east shore of Naujat atât contains abundant small brown biotite flakes scattered through plagioclase and concentrated in small nests. The felspar sometimes shows a true brown clouding which cannot be resolved under the microscope. Other constituents are green hornblende, apatite prisms and accessory ore with sphene reaction rims. The mass is intruded by veins from the surrounding Julianehåb Granite at its southern margin and on its north side appears to have been altered by permeating material derived from the granite, but it bears no resemblance in hand-specimen to the hornblendic gneisses described in Section II(c). It is traversed by irregular dark-green veins containing abundant sodic plagioclase, green amphibole and diopside (30073) and is cut by a $^1/_4$ m wide basic Gardar dyke with small felspar laths fluxioned parallel to the length of the dyke. Other veinlets consist of epidote centres and thin amphibole-rich margins. Parts of the mass, dusty with released ores, have been highly recrystallized or mineralized. They bear granular pale green diopsidic pyroxene and nests of green amphibole surrounded by diopsidic zones; felspar is recrystallized to a fine-grained aggregate containing occasional relics of original felspar. Similarly altered fine-grained microphyric basalt veins cross these areas and the rest of the mass. Angular interstices in the breccia are filled by green amphibole and diopside.

(b) Regionally metamorphosed dykes of E. Alángorssuaq.

Numerous metamorphosed dykes, usually about 1 m wide though some are several metres thick, cutting the hornblendic gneisses, agmatites and other Julianehåb Granite phases but cut by Gardar dykes, are found throughout E. Alángorssuaq. They dip at all angles between 45 and 90 degrees, lack chilled edges and are characteristically impersistent, lenticular. Individuals generally vary considerably in attitude. Most trend N.-S. or N.N.E. parallel to the planes of shearing mentioned in

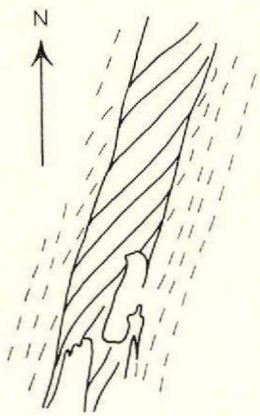


Fig. 10. Metamorphosed dyke about $^1/_2$ m wide, E. Alángorssuaq, seen in horizontal surface. The lines striking east of north indicate the direction in which lenticular biotite-hornblende aggregates a few mms long are orientated in the dyke. Broken lines indicate *s* planes in the adjacent Julianehåb Granite, continuous with the *s* structures in the dyke.

Section II (d) (i) by which they are affected and to which their irregular form can be largely ascribed.

In hand-specimen they are fine-grained dark gray or greenish-coloured rocks. The majority are aphyric but some contain felspar phenocrysts up to a few cm long. A number bear vague ramifying areas paler and richer in felspar than the enclosing rock. In some dykes (e.g. 30029, a very thin N.-S. dyke) biotite and green hornblende as well as occurring in the groundmass also form lenticular aggregates a few mm long aligned in parallelism as in fig. 10. The groundmass biotite and hornblende may or may not show preferred orientation; in certain dykes they are aligned parallel to shear planes in the adjacent Julianehåb Granite.

Fourteen dykes were examined in slice. A small minority are essentially green hornblende with or without brown biotite. The rest contain abundant xenomorphic oligoclase or andesine which, unlike the felspar

Fig. 11. Dyke attacked by reactivated Julianehåb Granite: see text. G.G.U. Photo. W.T.H.

in many Gardar dykes, is devoid of clouding. Green hornblende (Z = bluish green) and brown biotite are plentiful. Small sphene grains are common; other accessories are disseminated tiny pistacite granules, quartz, interstitial alkali felspar, and thin minute apatite prisms. Ore is often absent.

These dykes have obviously been recrystallized but they can be distinguished from the strips of Green Schist in the Julianehåb Granite for some contain inclusions of the granite, others have felspar-phyric centres but aphyric margins, and the felspar phenocrysts in certain porphyritic examples are aligned parallel to the length of the dyke in which they occur.

Field relationships are well displayed in the clean tide-swept coastal exposures of E. Alángorssuaq. Here the margins of some N.-S. dykes (e.g. fig. 10) are clearly related to the sinistral hot shearing mentioned in Section II (d) (v) and sometimes thin out into wisps of biotite and hornblende following shear planes in the granite. Due west of the centre of Qeqertarssuánguaq, among several small schistose dykes near loc. 1 on fig. 2 one trending N.N.E. and 1.5 m wide contains small felspar phenocrysts up to 1 cm long and epidotic nodules in a green hornblende-albite ground. Its margins are highly schistose and bear diopside and epidote bands up to 1 cm thick concordant with the schistosity. This banding and schistosity is microfolded. The dyke is traversed by microveinlets of pistacite and contains a small lenticular inclusion of Julianehåb Granite that, although fairly coarse-grained, has been plastically sheared. The adjacent granite (30006) is of normal type and displays innumerable shear planes parallel to the dyke, marked by granulation of quartz and felspar. Small green hornblende and brown biotite crystals grow across the shear planes.

A similar dyke nearby (30007), trending N.N.E. and 10 m wide, is marginally sheared. The adjacent Julianehåb Granite is of normal type and encloses numerous elongated fragments of the dyke which have ragged, and occasionally black, amphibole-rich margins.

In the same neighbourhood at a small promontory an early dark dyke, involved in the shearing on N.N.E.-trending planes that has been noted, is extensively attacked by the Julianehåb Granite (fig. 11). A later metasomatism has affected the latter which is a pink rock that has lost all its quartz and is now chiefly albite in 1—2 mm long crystals set in a granulated base; a little microcline, some diopside, and veinlets of colourless fluorite enclosing garnet occur.

(c) Dykes in the vicinity of Josvaminen.

In view of the particular interest of the Josva locality its dykes merit separate description. The most remarkable is that (marked '*a*' in fig. 12) which has irregular sometimes demonstrably vertical contacts and forms oval-shaped inclusions from one to several metres long in the syenite. The last sends lobate protrusions up to 1 metre long into the dyke and, as previously mentioned, the granulation surfaces in the syenite may either follow or be truncated at right angles by the contact of the dyke. In the field the dyke is bluish-gray, fine-grained, aphyric and irregularly jointed. Its margins show a reaction zone several cms thick (fig. 13) conspicuously paler in colour than the rest of the dyke and brecciated in a few places. A thin-section several cm long cut across this zone (39525) shows the following, passing from the syenite into the dyke. The syenite contains scattered diopside crystals ($\alpha = 1.67$, $Z \wedge c = 43°$) sometimes slightly bent and often concentrated in small aggregates, which together with porphyroclasts of perthite and albite (with or without chess-board structure) are set in a fine-grained granulated felspathic base. Towards the dyke diopside increases, pistacite appears, granulation is intensified and the coloured minerals tend to form fine-grained streaky aggregates running parallel to the dyke. This is the pale megascopically conspicuous reaction zone seen in fig. 13. It gives way abruptly to the dyke which is a thoroughly recrystallized very fine-grained aggregate of abundant sodic plagioclase, plentiful green

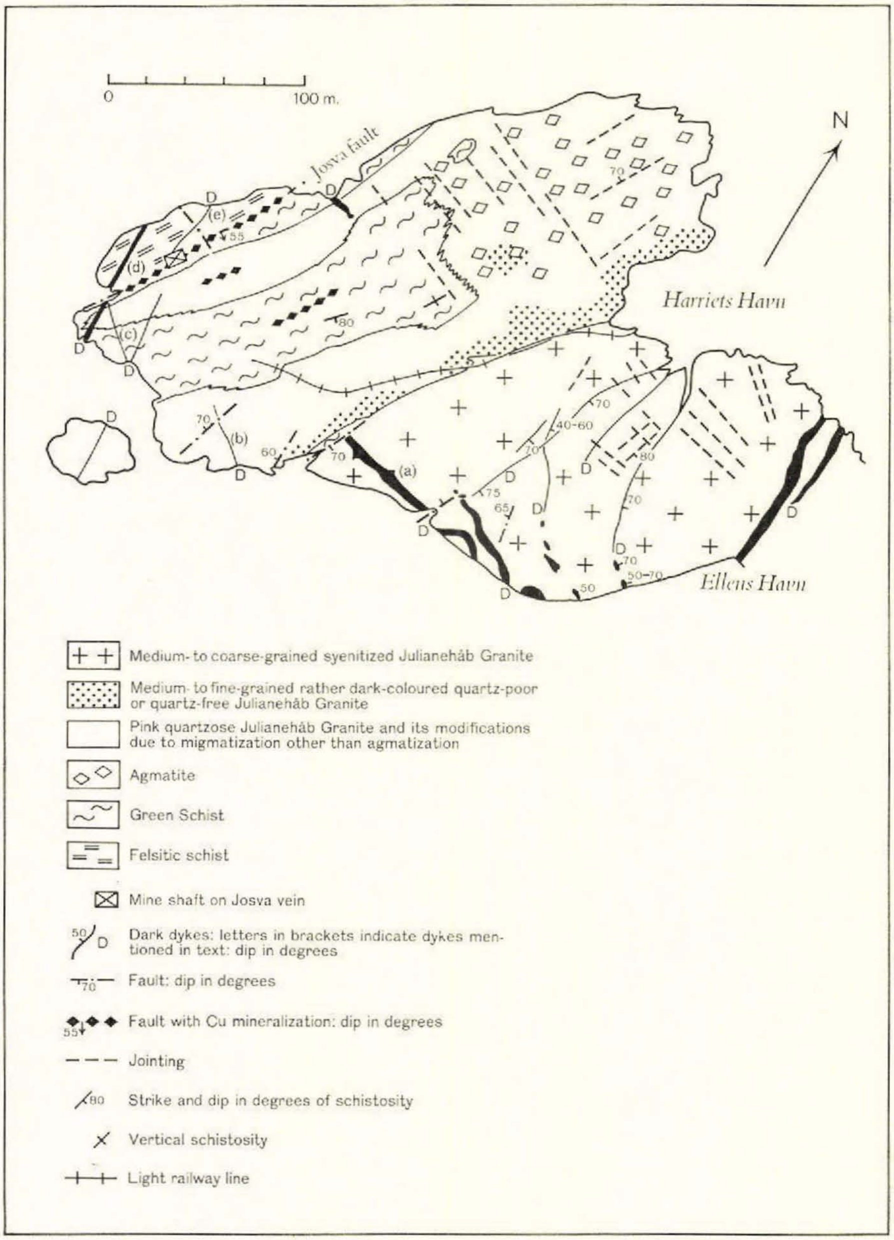


Fig. 12. Geological map of the peninsula at Josvaminen. Topography from air photographs taken by Prof. A. Berthelsen, and from ground control.

hornblende and brown biotite in parallelism, some diopside, epidote, disseminated tiny ore grains, sphene and quartz.

On the south shore of the Josva peninsula there are also oval remnants of another altered dyke that runs northwards through the syenite

Fig. 13. Metamorphosed dyke at Josvaminen penetrated by lobes of syenitized Julianehåb Granite (see text) one of which (with the camera at its upper extremity for scale) seems isolated but is actually connected with the main syenite mass. A pale reaction zone a few cm wide occurs at the contact of the dyke. G.G.U. Photo. W.T.H.

(see fig. 12) and resembles dyke '*a*' in slice. One example (39538) is considerably mineralized, containing abundant diopside, and garnet as veinlets or disseminated grains.

Other thin altered dykes also occur in the syenite. Some contain small crystals and aggregates of green hornblende in a fine-grained felspar—biotite—green hornblende base and resemble certain of the Kobberminebugt Green Schists but their dyke origin is apparent from their persistency and the fact that two cross each other in the centre of the peninsula. They show slight marginal metasomatic alteration.

About 50 m west of the western termination of dyke '*a*' a recrystallized 50 cm wide vertical gray fine-grained dyke ('*b*' on fig. 12) (39529) contains green amphibole and brown biotite with preferred orientation: plagioclase phenocrysts about 1 mm long set at various angles to this schistosity have been disrupted and invaded by the fine-grained granular felspathic groundmass. Where the dyke is cut by a N.N.E. fault it bears garnet showing anomalous birefringence in zones (probably grossularite) fluorite, pistacite, diopside, scapolite, alkali felspar (39530).

Dyke '*c*' on fig. 12, rich in hornblende and biotite, is less than 1 m wide and has the same N.W. trend as dyke '*b*'. It shows a foliation continuous with banding in the adjacent schists. Ussing states in his notes that at very low tides it is seen to be cut by the dark dyke '*d*' which is 1—1.5 m wide and is slightly deflected in its course at the Josva fault. Dyke '*e*' is difficult to trace owing to mine-waste; near the north-west coast it bifurcates. A dip of about 65° S.E. can be seen at one place. Like the others it is dark in colour and fine-grained. As remarked by BERTHELSEN (1958) the probable chronology of these dykes is as follows. The oldest appears to be dyke '*a*'; some of the other metamorphosed dykes in the syenite and dykes '*b*' and '*c*' may be younger. The N.-S. dykes '*d*' and '*e*' are relatively unaltered and considering USSING's observation appear to be youngest of all. They may be of Gardar age.

The *lit-par-lit* migmatites near Lilianminen described in Section II are cut by a small slightly folded dyke (39557) consisting of highly saussuritized indeterminate xenomorphic plagioclase crystals a few mm long in a fine-grained xenoblastic ground of clear sodic plagioclase, green hornblende and dark brown biotite, the last two showing preferred orientation. Minute sphene grains are abundant, some quartz occurs in the groundmass and a little ore is present.

(d) Gardar dykes and ? Tertiary dolerite dykes.

Numerous Gardar dykes, most of which are thin, cut the basement and many of the metamorphosed dykes described above. The majority are basic, a few are trachytic and there are occasional felsites. They post-date the N.N.E. shearing that affected the Julianehåb Granite. This is particularly evident in the case of those small basaltic dykes (e.g. 30010) with chilled edges that trend E.S.E., tend to occur in minor swarms, contain numerous thinly tabular felspar phenocrysts a few mm long, and often clearly cut epidotic mineralized shears in the Julianehåb Granite of E. Alángorssuaq.

The detailed petrology of the Gardar dykes can be left to later descriptions. Here it is only important to note the features in which they differ from the dykes so far described: their trend is comparatively regular, fine-grained edges are common, felspars with true clouding are frequently present, schistosity and recrystallization—apart from uralitization—are lacking.

Dolerite and olivine-dolerite dykes perhaps of Tertiary age cut the Gardar dolerites. They are much less abundant than the latter, and are characterized by their rusty brown colour on weathering. Regularly jointed, they trend N.W. and possess chilled edges.

IV. GENERAL GEOLOGICAL EVOLUTION OF THE ALÁNGORSSUAQ BASEMENT

From the data provided the following broad sequence of events can be made out. The amphibolitic Green Schists represent an original series of Ketilidian sediments and basic lavas which were metamorphosed in the course of the Ketilidian orogeny. The conditions of metamorphism apparently hovered around the transition between the green schist facies and the amphibolite facies as defined by the association epidote-plagioclase An 30. Many of the epidote-rock bodies in the schists probably originated at this time, for some are incorporated in Julianehåb Granite migmatites and epidote developed as abundant disseminated grains in the schists during the Ketilidian metamorphism.

The dark hornblendic gneisses seem also to have been metamorphosed at the same time. They are texturally dissimilar from and more coarsely recrystallized than the minor basic intrusions altered in ? Sanerutian times, and at one locality (see Sect. II b) comparable rocks are intimately associated and appear contemporaneous with Green Schists. Some of the felsites described in Sect. II (e) (i) may also be contemporaneous with the schists, for similar felsite forms a block in agmatite near Josvaminen.

At the close of the Ketilidian orogeny the Julianehåb Granite was emplaced, migmatizing the schists and hornblendic gneisses. There is much evidence that replacement processes were important in forming these migmatites. A striking example, as BERTHELSEN (1958) has noted, is the agmatite at Josvaminen (figs. 4—6). In this mass there are all transitions from normal schists to completely granitized rocks, the lengths and schistosity of the relict blocks are parallel to the strike of the similar schists into which the agmatites pass approaching Josvaminen, and the general field impression is one of isovolumetric granitization under static conditions. It should be noted, though, that SUDOVIKOV (1955) has illustrated comparable agmatites from Karelia but has ascribed the parallelism of the blocks in them to movement.

Although the granitization seen in migmatites peripheral to, and also within the outcrop of, the Julianehåb Granite raises the question of a replacement origin for the normal granite, it is not in itself adequate reason for rejecting a magmatic hypothesis. Moreover, the metamorphic textures of the granite are not proof of replacement, for they could be due to recrystallization of igneous rock. The original nature of the normal granite has been obscured by later events and could have been largely magmatic. Many of the felsites described in Section II (e) (i) seem late aplitic phases of the normal granite locally modified by shearing, mylonitization and metasomatism.

The dark porphyritic (or porphyroblastic) variety of Julianehåb Granite seems due to basification of the normal granite through reaction with the schists, for it is often associated with agmatites and passes into normal granite. The pale medium-grained granite mainly found east of Nyboes Kanal was intruded at some later date, perhaps in connexion with Sanerutian remobilization but the evidence critical for this lies outside the area described.

Swarms of thin, now metamorphosed, basic dykes intruded the normal and basified granite. During a phase of remobilization the older members of these swarms were attacked by reactivated granite. Similar phenomena are known in other parts of the world; an example has been described by Oftedahl (1953). To the same general ? Sanerutian period belongs the recrystallization of the dykes and their country rocks, which probably happened at various times separated by dyke emplacement. Shearing along N.-S. or N.N.E. trending lines may have accompanied its waning stages. Sutton and Watson (1959) have described rocks deformed by transcurrent movements during regional metamorphism, though the intensity and depth of cover involved were much greater than in the suggested Alángorssuaq instance.

Since the metamorphosed dykes in E. Alángorssuaq roughly coincide in trend with the deformation planes in the surrounding granite, the question arises: were they intruded during and not before the movements that have effected them? The answer seems to be negative. This agreement in trend seems either largely coincidental or due to control exerted over later movements by pre-existing structures, for some undoubtedly Green Schist lenses are similarly orientated, and some metamorphosed dykes show mineral parallelism in their groundmass but not in their felspar phenocrysts. Furthermore, relatively felspathic patches found in certain dykes have irregular outline, appear to be magmatic segregates, yet do not form orientated lenses as they would be expected to do if the dykes had been syntectonic intrusions.

A later metasomatism is evident at many places throughout the Alángorssuaq basement, the most striking results being albitization and desilication of the normal Julianehåb Granite. Other effects were appearance of diopsidic pyroxene instead of amphibole, and formation of haematite, epidote, and a garnet apparently rich in grossularite.

These metasomatized rocks throw light on the origin of chess-board albite (*Schachbrettalbit*), the interesting blocky structure due to a complex pattern of interrupted albite twin lamellae seen in certain albite crystals and first described by BECKE (1906 pp. 124—5) who ascribed it to replacement of microcline, a view shared by some later workers though others favour a primary origin. STARKEY (1959) has provided a useful review of the relevant literature and has discussed the origin of the structure.

Chess-board albite in the metasomatized Julianehåb Granite is clearly of secondary origin. It mainly formed by soda metasomatism of microcline under the influence of stress, for evidence of syntectonic crystallization is common. This, essentially, is the origin proposed by STARKEY (op. cit.) for chess-board albite in certain rocks from New Brunswick and Britain. These conditions, however, were not absolutely essential for chess-board albite formation. Occasional chess-board albites in the Julianehåb Granite seem to have resulted from replacement of slightly more calcic plagioclase. Chess-board albite without signs of syntectonic crystallization and deformed albites without chess-board structure can occur in the metasomatized granite. In the syenite roughly 1—2 km S.W. of Rinks Havn twinned albite lacks chess-board structure in the slices examined, though it must be pointed out that the albites here are smaller than, and do not show such highly deformed lamellae as, those in the other syenites with conspicuous chess-board structures. Moreover the soda metasomatism does not seem to have been as intense as in the latter.

The soda metasomatism has not conspicuously modified the grain size of the rocks it affected. Its syenitic products are medium-grained like the parental granite into which they pass. The syenite at Josvaminen and the darker, finer-grained migmatitic granite on its northwestern margin, which has likewise undergone soda-metasomatism, are distinct and their contact has not been appreciably blurred by metasomatism. The sharpness of their contact seems due to movement of one member or the other during the Ketilidian migmatization and has been preserved by subsequent metasomatism. Moreover, aplitic or felsitic veins affected by soda metasomatism retain their grain size. So it is most unlikely that the soda-metasomatism has been responsible for generating noteworthy felsitic or syenitic rocks from Green Schists. It would seem incapable of effecting such a thorough reconstitution of the parental rocks.

Thus dyke '*a*' at Josvaminen, into which the syenite sends thin lobes and which forms ovoid remnants in the syenite, is believed to have been attacked not by the syenite but by the Julianehåb Granite during (probably Sanerutian) remobilization as were some of the dykes in S.E.

Alángorssuaq. Later metasomatism syenitized the granite but had little effect on the dyke boundary. Its main effects at the dyke margin were simply production of thin reaction rims rich in diopside and grossularite.

The age of the soda metasomatism raises a difficult problem. At Josvaminen penetrative movements during the metasomatism impressed crude planar structures on the syenitized Julianehåb Granite (but did not involve unrestricted transport for several thin earlier metamorphosed dykes in the syenite can be traced right across the peninsula without showing disruption). Most of these planar structures are not highly dissimilar in trend from those of ? late Sanerutian age in the Julianehåb Granite of E. Alángorssuaq (see Section II (d) (i)) but this agreement is probably coincidental and not indicative of age equivalence. As will transpire, the syenitization at Josvaminen may be a preliminary phase of a copper mineralization which took place at much shallower depths than those at which the ? Sanerutian metamorphism could have arisen, assuming normal geothermal gradients, and could be Gardar (Sect. VIII). Whether all the soda metasomatism seen in the Alángorssuaq basement is the same in age is a question briefly discussed in Sect. V (h).

V. OCCURRENCE OF COPPER ORES AND ASSOCIATED MINERALIZATION

This section deals with the products of the processes that ultimately yielded the copper ores at Josvaminen, and concludes with a brief discussion of the relation between those phenomena and certain metasomatic effects already described in this paper.

(a) Metasomatized migmatites near Josvaminen.

Migmatites on the Josva peninsula affected by the mineralization there tend to lose quartz, and develop albite together with some garnet, epidote, diopside and other minerals associated with the Cu ores. They are, however, neither notably altered in grain-size nor migmatized by this metasomatism.

Near the foundations of the ruined building in the north-east part of the peninsula the Julianehåb Granite has a vaguely patchy migmatitic appearance that may be largely or wholly due to crushing and mineralization. In slice (39546) it shows abundant oligoclase crystals up to 2 mm long, with bent and ruptured twin lamellae, plentiful quartz in medium-grained polycrystalline areas, a little microcline, some brown biotite and green hornblende, epidote, diopside and garnet. The last fills cracks in plagioclase, encloses granulated quartz crystals and, associated with sphene, follows planes of shearing. Its late origin is thus obvious.

Another sample of the same granite (39547) a few metres from the last contains little or no quartz, abundant albite-oligoclase and a little microcline; olivine-green biotite, diopside, garnet and sphene tend to be concentrated in irregular patches. Apatite and calcite are accessory.

A rock from the agmatites north-east of Josvaminen consists predominantly of albite, mostly very fine-grained and granular but also as larger crystals up to 1 mm long, showing mortar textures, undulatory extinction, and cracks healed by fine-grained albite. Strongly corroded crystals and aggregates of green hornblende may occur; isolated grains, streaky aggregates or thin discordant veinlets of pistacite and zoisite are common. Magnetite, sphene, and apatite are regular accessories; quartz is scanty.

An aplitic veinlet in the migmatitic schist near Josvaminen is largely potash felspar and albite of variable grain size (up to about 0.3 mm) sometimes locally forming anhedral poikiloblasts about 1 mm across enclosing patches of the fine-grained groundmass. Garnet is commonly interstitial to felspar but also forms porphyroblasts or glomeroblasts. Calcite occurs interstitially, usually associated with garnets. Epidote, sphene, and diopside occur in streaks and nests mainly near margins of the veinlet. A fibrous, pale green amphibole and magnetite are mostly interstitial to garnet. Apatite is accessory and quartz is absent. Other samples from the same locality have essentially the same composition and textures though biotite and some quartz may also occur and some of the larger potash felspar grains may be perthitic: In addition a few disseminated grains of bornite, chalcocite, and pyrite may be present.

A migmatitic rock (39526) passing into normal granite on the S.W. shore of the Josva peninsula is almost wholly albite with deformed twin lamellae: small amounts of diopside, green hornblende, pink sphene and ore occur. It is finer-grained and darker than the syenite forming the neck of the peninsula described in Section II and resembles the rocks (e.g. 39541) occurring along the N.W. margin of that syenite, (see fig. 12) which are chiefly twinned (occasionally chess-board) albite, lack quartz and sometimes contain small irregular granules of late garnet, diopside and epidote following crush lines. Similar rocks that occur on the west shore of Harriet's Havn contain chess-board albite (formed in the same way as that discussed in Section IV) and dark agmatitic inclusions some of which show thin vague rims of a blue-weathering asbestiform amphibole, pleochroic deep bluish-green to brownish tints 2V (—), $Z \wedge c = 20°$. The inclusions have ragged margins and their matrix contains thin wisps of the asbestiform amphibole.

Ramifying microveinlets at this locality have carbonate centres, with some garnet, and margins rich in ore grains. The carbonate is moulded onto (010) plagioclase faces and the garnet can be coated with ore. This calcite—garnet—ore association is later than the albitization and obviously part of the copper mineralization at Josvaminen.

The acid component of a *lit-par-lit* migmatite close to and S.W. of the machine house at Josvaminen has abundant quartz and oligoclase; mortar structures are extensive and epidote, garnet and diopside are common products of mineralization (39534).

(b) Metasomatized Green Schists near Josvaminen.

A dense network of epidotic replacement veinlets cuts the amphibole-schists near and north-east of Josvaminen. The thinnest veinlets (up to 1 mm thick) are often straight, intersect each other without—or with only slight—offset and seem to have formed along thin cracks. Veinlets 0.5 cm or more thick show clear evidence of replacement—intersections without offset; irregular variations in thickness and comb-like margins; pronounced thickening at intersections. Fig. 14 shows an epidote veinlet following a small fault marked by small pockets of euhedral garnet, scapolite, epidote, diopside, actinolite, bornite, chalcocite and occasionally other minerals. The veinlet has comb-like margins

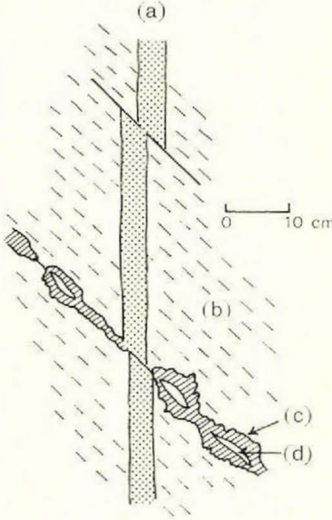


Fig. 14. Epidote veinlet in Green Schists N.E. of Josva's vein; Josvaminen. — (a) felspathized acid veinlet, (b) Green Schists, (c) epidote replacement zone, (d) open fissure fillings with garnet, scapolite, some epidote, bornite, chalcocite.

which, together with the way in which the associated felsitic veinlet has resisted epidotization, clearly show its replacement origin.

Under the microscope the epidotic veinlets mainly consist of granular fine-grained (av. grain-size about 0.1 mm) pistacite, and enclose some relict biotite- and amphibole-schist areas. The central parts of the veinlets can contain one or more of the following: euhedral garnet (up to 1 mm in diameter), scapolite (from 1 mm to 2.5 cm long), prehnite, diopside, actinolite, sphene, alkali felspar (sometimes apparently replacing scapolite and epidote), interstitial bornite, chalcocite, and sometimes also galena. The adjacent schists consist of a blue-green amphibole, biotite, and epidote, the last often following shear planes sometimes transecting amphibole crystals which may be recrystallized into a fine-grained aggregate on the shears. Epidote rapidly becomes more abundant as the epidote veinlets are approached and in places forms rounded aggregates 1—3 mm in diameter.

Small epidotic nests, nodules, streaks and veinlets are rather abundant in the schists below the footwall of the Josva vein. Some show concentric banded structures (fig. 15) as follows. Their coarser-grained central parts may consist chiefly of actinolite but euhedral garnet aggregates with or without scapolite are equally frequent, the scapolite forming radiating prisms up to 3 cm long to which garnet is interstitial. Calcite, potash felspar and some albite are interstitial to actinolite, garnet and scapolite, the last three minerals showing signs of partial replacement. Other minerals that can occur are sphene, epidote, apatite, bornite,

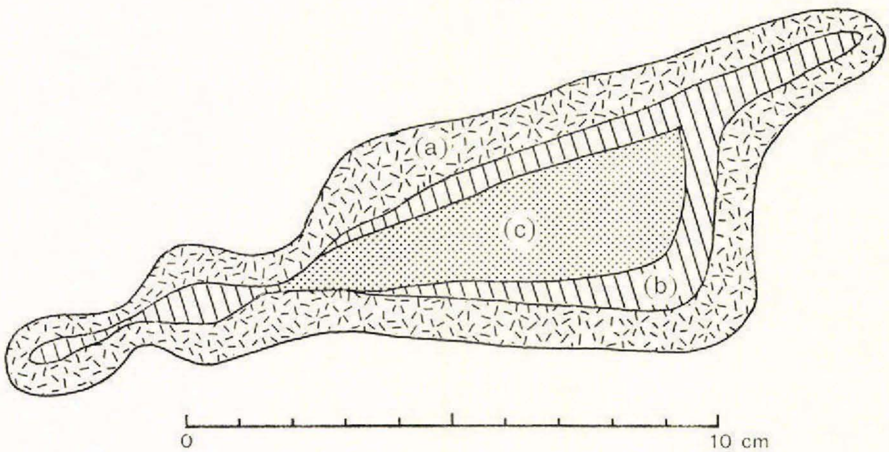


Fig. 15. Banded mineralized vug in felsitic schists west of Josva's vein; Josvaminen: (a) pink fine-grained felspathized zone of alkali felspar; some magnetite, (b) pale green epidotic zone; largely epidote, some actinolite, calcite, apatite etc., (c) coarse-grained actinolite with some interstitial bornite and chalcocite.

chalcocite, the copper sulphides being found on cleavage planes, cracks and the boundaries between other minerals. An intermediate green zone consists mainly of fine-grained pistacite; a little actinolite, garnet, sphene and apatite can occur. Usually there is an outer pink rim chiefly composed of anhedral potash felspar (av. grain size 1 mm) which can show microcline twinning, highly subordinate albite, and euhedral magnetite, sometimes in aggregates.

The mylonitized ('felsitic') schists in the footwall of the Josva vein described in Sect. II (e) also frequently contain fissures and vugs crossing and plainly later than the shearing and filled with alkali felspar, epidote, large sphenes, diopside, garnet, scapolite calcite, and actinolite. Veinlets up to a few cms thick of perthitic twinned microcline are common, as in the adjacent schists. Andesine porphyroclasts in the felsitic schists often bear clear alkali felspar rims, and the same rocks show numerous bands of albite, or albite and microcline, or microcline alone. Felspathization is well developed along the fault mineralized by the Josva vein.

(c) Epidotization and mineralized epidote-rocks at localities other than Josvaminen.

In the schists along the coast west of Lilianminen fine-grained granular epidote-rocks with some quartz, sphene, apatite and actinolite form streaky bands and veinlets which can attain a thickness of 40 cm and a length of 10 m. They are mostly concordant to the foliation of the schists but can be discordant, and many are traversed by fracture fillings (fig. 16). The last mainly consist of coarse-grained quartz, but

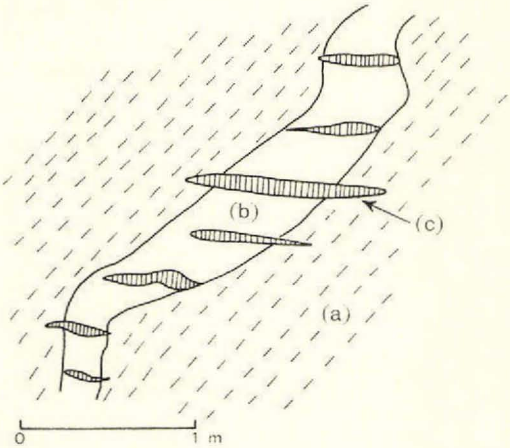


Fig. 16. Epidote-rock streak (b) in Green Schists (a) west of Lilianminen. The streak is traversed by fracture fillings (c) containing alkali felspar, haematite, quartz, actinolite, bornite, chalcocite.

haematite flakes 1 mm—2 cm long are abundant and may form aggregates sometimes surrounded by small sphene grains. Actinolite needles, often in radiating aggregates, occur especially along the walls of the fissure fillings and euhedral alkali felspar accompanies the quartz. Epidote crystals are much larger than in the epidote rocks. Some interstitial chlorite, bornite and chalcocite may also be present.

The minerals found as fissure fillings can also be concentrated round epidote nodules as a light-coloured rim in which alkali felspar and haematite are often the most prominent constituents.

From Lilianminen to Rinks Havn along the shores of the Kobberminebugt similar phenomena are seen from place to place. Some epidote-rock lenses and folia in the Green Schists bear irregular fracture fillings comprising one or more of the following minerals: microcline, albite, calcite, pistacite, sphene, asbestiform amphibole, diopside, haematite plates, apatite, light-brown garnet. These minerals can also form rims round epidotic rock bodies and fill small isolated fissures in the schists.

Thin films of secondary green and blue copper minerals can coat the foliation planes of the associated schists.

Near Rinks Havn the mylonitized Julianehåb Granite close to the schists is traversed by epidote replacement veinlets that are clearly later than the shearing.

Fig. 17. Quartzose lenses in Green Schists near Lilianminen. See text for explanation. G.G.U. Photo. W.T.H.

(d) Metasomatized quartzose lenses near Lilianminen.

Towards the tip of the small peninsula close to Lilianminen Green Schists with steep planar foliation contain leucocratic folia and lenses up to $^1/_3$ metre thick, separated by thinner folia of schist without marginal reaction zones. Vertical and horizontal surfaces combined demonstrate that several of the larger lenses are lenticular in both vertical and horizontal planes and thus are isolated bodies within the schist. Examples are shown in fig. 17. The schistosity of the enclosing rock is deflected slightly round the lenses but insufficiently to conform with their margins. The pods illustrated lie within a layer of hornblende-schist sandwiched between two thin parallel fine-grained gray ribs which do not diverge round the pods. Whether these ribs are integral parts of the supracrustal sequence is uncertain. Certainly they have been regionally metamorphosed: one (39555) is a green hornblende-biotite-albite rock in which the dark minerals show a preferred orientation. But they contain scattered small plagioclase phenocrysts sometimes recrystallized to granular aggregates, and are not unlike some metamorphosed basic dykes, so that they may possibly be later than the Ketilidian migmatization.

The pods show a patchy distribution of minerals and mortar structure is common. Quartz is abundant, rather fine-grained, and shows highly intricate crystal boundaries. Oligoclase is common and often contains numerous quartz and potash felspar blebs: its twin lamellae are not deformed. A little potash felspar occurs in the groundmass. In some samples a delicate network of alkali felspar follows the grain boundaries of the quartz crystals. Hornblende (Z = bluish green) can form radiating aggregates. Moderate amounts of brown biotite and epidote are present. There may be a little diopsidic pyroxene and garnet, as in the Josva migmatites, and sphene; apatite and magnetite are accessory. In one sample from the centre of a pod chess-board albite porphyroblasts enclose groundmass quartz.

Many pods bear pink felspathized margins 5—10 cm broad enriched in alkali felspar and often containing albite porphyroblasts up to 1 mm long.

The adjacent schists contain green hornblende (Z = bluish green) brown biotite (often with numerous small epidote inclusions) potash felspar, and a little diopside in a quartzo-felspathic ground. Prehnite can be present. Some samples show traces of copper mineralization. Thin felspathic folia and lenticles are present and one consists mainly of very fine-grained anhedral albite with some interstitial potash felspar; saussuritization and sericitization are common; amphibole and epidote occur as scattered grains or concentrated in streaks and nests; sphene, prehnite, diopside, garnet, apatite and a little bornite may occur.

The pods appear to be either Ketilidian replacements of schist or quartzose ribs in the metasedimentary sequence which have been dragged into lenses during Ketilidian deformation and subsequently felspathized in association with the nearby copper mineralization.

(e) Mineralized pegmatitic veins.

Along the shore 1—2 km S.W. of Josvaminen there are a number of pink, fluoritic, pegmatite veins up to about 0.5 m thick in which Ball (1923) noted bornite and chalcopyrite masses up to 1.2 cm broad. One vein, 35 cm thick (30188) dips gently, cuts a granitic vein of Ketilidian age traversing the schists, and in its felspars resembles some pegmatites of the Nunarssuit complex. It contains quartz, albite-oligoclase, some microcline-perthite, purple fluorite, and copper sulphides. The adjacent rocks show conspicuous copper staining. A similar vein (19628) nearby has been spectrographically examined (see Table I).

Table I.

Semi-quantitative Spectrographic Analyses.

	Sn	Pb	Ag	Cu	Zn	Co	Ni	Cr	Mo	V	Ba	Sr	Ti	La	Y	Ce
19628	÷	÷	< 10	3000	÷	÷	÷	÷	÷	÷	50	÷	100	÷	10	÷
19630	÷	÷	÷	300	÷	÷	< 10	< 10	÷	÷	1000	20	1 %	÷	÷	÷

Anal. IB SØRENSEN.

19628 — 20 cm pegmatite vein west of Josvaminen.

19630 — Haematite impregnation in major N.N.E. dextral transcurrent fault near and east of Josvaminen, shores of Kobberminebugt.

Other quartz-alkali felspar pegmatite veins, usually straight, 1—30 cm thick and apparently following discordant often subhorizontal fractures, sometimes contain one or more of the following: bornite with exsolved chalcopyrite, wittichenite, sphalerite, pyrite and magnetite; these ore minerals are interstitial to the other constituents. Molybdenite has occasionally been seen.

Pegmatites mainly composed of alkali felspar with or without quartz occur near Sorttop. Albite or microcline can predominate. The latter tends either to be interstitial to euhedral albite, or to form large crystals corroding albite. Perthites have not been observed. The veins contain some relatively fine-grained nests of one or more of the following: epidote, actinolite, calcite, prehnite, sphene, muscovite, chlorite, magnetite, haematite, bornite, chalcocite, fluorite.

Some pegmatitic veins in schists near Josvaminen consist predominantly of prismatic scapolite poikiloblasts about 1.5 cm long showing pronounced cataclasis and commonly containing xenomorphic albite inclusions. Calcite, garnet, epidote minerals, prehnite and sphene fill cracks in the scapolite and also form interstitial grains between scapolite crystals. Anhedral alkali felspar sometimes occurs.

(f) Copper mineralizations along faults and shear zones.

Important concentrations of bornite and chalcocite occur only along major fault and shear zones. At Josvaminen the main lode, the Josva vein, is a mineralized fault breccia: the fault is concordant, strikes

N.E.-S.W., dips 55 degrees S.E., and separates mylonitic felsitic schists in the foot-wall from amphibole schists in the hanging-wall. From foot-wall to hanging-wall the fault zone is about 130 cm thick and is divisible into the following parts (Fig. 18):

80—100 cm deformed felsitic schists, devoid of or very poor in Cu-mineralizations;
0—30 cm ore-rich zone; the ore occurs in lenses about 10×8×5 cm
10—20 cm fault breccia consisting of angular fragments of felsitic and; amphibole schists in a fine-grained, massive alkali felspar matrix and impregnated with bornite and chalcocite grains.

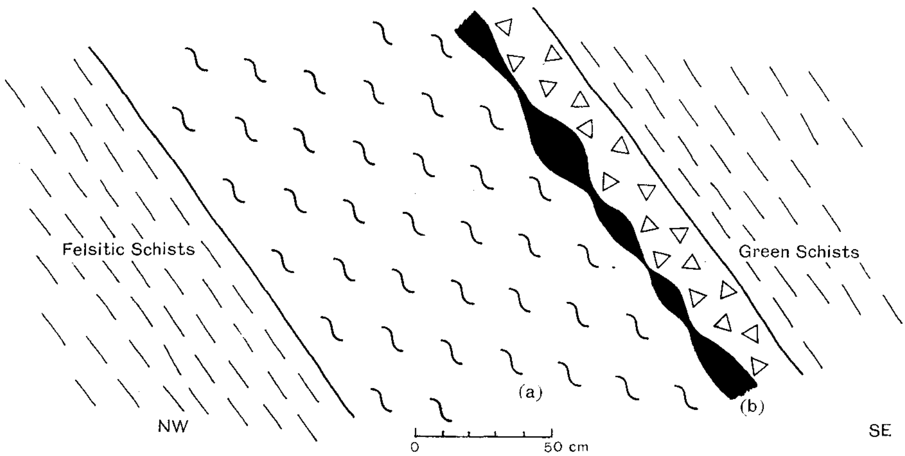


Fig. 18. A vertical cross-section through Josva's vein, Josvaminen: (a) deformed felsitic schists, (b) ore zone, (c) fault breccia.

The deformed felsitic schists are richer in potash felspar than their undeformed equivalents. Macroscopically they show a more schistose habit and microplications.

The ore lenticles consist of bornite with appreciable amounts of chalcocite and accessory ilmenite, magnetite, haematite, chalcopyrite, wittichenite, electrum and native copper. They contain streaks and nests of epidote and actinolite, the latter often in radial aggregates. The ore penetrates epidote and actinolite along cleavage planes and cracks. Actinolite in particular is conspicuously deformed, being bent and broken. It forms prisms with usually ragged ends apparently corroded by the ore, but its side-faces are usually not attacked and euhedral basal sections enclosed by ore are common. Garnet may occasionally be present in the epidote aggregates. Sometimes alkali felspars, also highly disrupted and penetrated by the ore, occur in the ore lenses. One euhedral prismatic crystal of quartz has been found enclosed by bornite.

Alkali felspars, actinolite, or epidote often form narrow rims round ore lenses and alternating streaks parallel to the ore lenticles.

The fault breccia is heterogeneous in composition and texture. It contains angular fragments of a very fine-grained felsitic rock chiefly comprising alkali felspar. Highly deorientated fragments of amphibole schists, more or less altered and recrystallized and consisting mainly of fibrous actinolite, occur in a groundmass of alkali felspar with some sphene, epidote and magnetite. Subhedral albite laths in this matrix appear corroded by interstitial potash felspar, and anhedral porphyroblasts and glomeroblasts of K felspar enclosing corroded albite fragments occur. Actinolite occurs as numerous fine needles evenly distributed throughout the rock and often enclosed by felspar. It also forms fibrous aggregates apparently corroded by felspar. Albite-rich samples may contain appreciable amounts of euhedral garnet. The alkali felspars, actinolite, and garnet may be replaced by nests and streaks of pistacite. Appreciable amounts of sphene and larger actinolite needles of an apparently later generation may be associated with the epidote. These epidote-actinolite-sphene aggregates can be attacked by a fine network of ore veinlets following grain boundaries, cleavage planes and cracks.

Under the microscope, parts of the alkali felspar matrix of the fault breccia exhibit angular or subangular patches (0.1—2.5 mm in size) of alkali felspar (mainly potash felspar) cemented by a mass of fibrous actinolite.

Chlorite and fluorite, obviously later than the ore, form streaks and nests sometimes obviously filling voids, sometimes following the boundaries between ore masses and other minerals.

Textures and structures indicate that in the Josva vein movement recurred during early phases of mineralization but ceased before most of the ore was deposited.

About 75 m east of the Josva vein two other mineralized fault zones have been explored by underground workings. The latter are now inaccessible but the veins in them are probably lean. A mineralized discordant shear zone is also found along the edge of a N.-S. dyke a few metres S.W. of Josvaminen, associated with sphene, epidote, and apatite. The ore forms irregular veinlets, often tending to form rims around the felspar fragments. Fibrous actinolite replacing the alkali felspar fragments locally obliterates this brecciation. Ore minerals in the fault breccia are concentrated along the later cracks and shear planes. The felspathic matrix of the breccia may show an irregular network of thin veinlets of ore, often conspicuously associated with large actinolite crystals up to 3 cm long.

At Lilianminen, the presumed S.W. prolongation of Josva vein is bordered on both sides by amphibole schists. The fault zone is much thinner and lacks the bornite-rich zone with ore lenticles. It is marked by a strip of strongly sheared schists impregnated with alkali felspar, epidote, garnet, and actinolite. Bornite and chalcocite occur especially in the actinolite streaks and nests, but are also sparingly found interstitially between the other minerals. Locally a fault breccia consisting of coarse, angular Green Schist fragments cemented by a quartz groundmass is found. Unlike their quartz matrix the Green Schist fragments contain epidote and alkali felspar veinlets and streaks; brecciation and cementation by quartz seems later than felspathization, epidotization, and related mineralizations.

Ball (1923, p. 33) and Bøgvad (1950, p. 104) report that the ore in the mines decreases with depth.

A number of smaller shear zones are found in the area west of Lilianminen. They show only traces of copper mineralizations and are sometimes bordered by thin zones of felsitic rock.

(g) Copper mineralization filling joints and fractures.

Mineralized joints and fractures occur in Green Schists, Julianehåb Granite and dykes. Some examples have already been incidentally noted in describing associated phenomena. Epidote is the most conspicuous component and forms crystals up to 2 cm long, often associated with haematite plates up to 1.5 cm long. Other common constituents are actinolite, alkali felspar, fluorite, chlorite. Calcite, garnet and quartz can occur. Bornite and chalcocite, occasionally as regular intergrowths, are present, especially in association with actinolite. Some fissures bear thin marginal zones of epidotized wall-rock a few mm thick.

In dyke *d* on fig. 12 a number of fracture-fillings a few mm wide run roughly parallel to the strike of the dyke. They comprise bornite, chalcocite, alkali felspar and pale-green amphibole (e.g. 39565) and are surrounded by zones a few cm wide, leached of dark minerals, consisting largely of altered felspar with abundant tiny sphene grains.

A few veinlets up to 1 cm or so wide occur within dyke *a* on fig. 12. Chiefly composed of garnet (mostly isotropic) they also contain some diopside, albite (sometimes with chess-board structure) and apatite; small chalcocite-bornite lenses occur in their centres. In hand-specimen these veins are pale in colour but lack the faint greenish tint of the reaction zone at the margins of the dyke described in Section III (c).

Several crush-zones affect the Green Schists on the shores of Kobberminebugt west of Rinks Havn and strike sub-parallel to the *S* planes of the schist. Some are rusty-weathering and contain radiating aggregates of stilbite and asbestiform amphibole. They can also show thin films of secondary green copper minerals accompanied by pink felspar and quartz.

(h) General sequence of mineralization.

The various mineral parageneses are closely related in time as well as space. Nevertheless they seem to have reached their maximum developments at different periods as represented on Table II.

Mineralization began with extensive alkali metasomatism accompanied by deformation. Replacement by alkali felspar, largely albite, selectively affected quartz-bearing rocks and was accompanied by movement. In view of their close field association and mineralogical similarities it is reasonable to ascribe the felspathization of felsites described in Section II (e) and the soda-metasomatism producing the syenitic rocks in the neck of the Josva peninsula (Section II (d) v) to this phase. Whether or not all the other syenitic phases in the Julianehåb Granite described in the sub-section last mentioned and certain minor albite associations mentioned in Section II (d) (iii) should be also assigned to this phase remains an open question. It would not be surprising if alkali metasomatism has taken place more than once during the complicated pre-Cambrian history of the area.[1] Some of the soda metasomatism in E. Alángorssuaq seems associated with movements of pre-Gardar age, whereas the mineralized younger basic dykes at Josvaminen may well be Gardar.

However this may be, the formation of alkali felspar which took place intermittently throughout the course of mineralization at Josvaminen seems to have culminated at an early stage, clearly older than the calcite-garnet-ore association mentioned in describing metasomatized migmatites at Josvaminen and older than the epidotic replacements crossing felspathized felsites west of Lilianminen.

After cessation of the movements during alkali metasomatism a period of fracture ensued forming fissures in the Green Schists that became filled with garnet, scapolite, alkali felspar, prehnite, diopside and other minerals, whilst the adjacent schists were subject to intense epidotization. The fractures used by the mineralized pegmatites may have formed at the same time, as shown on Table II.

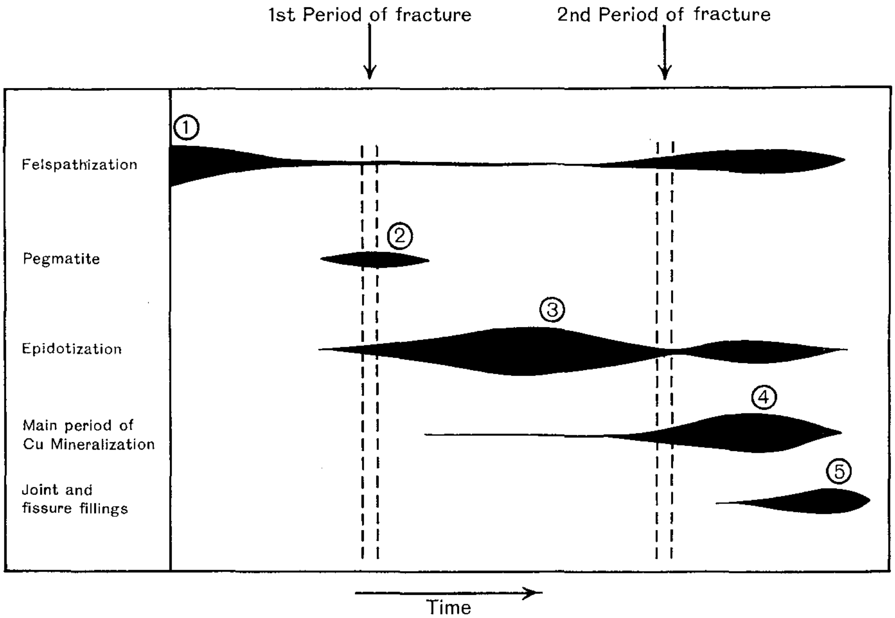
This main phase of epidotization took place under static conditions contrasting with the penetrative movements that affected relatively large areas of Ketilidian granitic rocks during the main episode of felspathization. It is possible that a considerable lapse of time separates the two phases. Although albitization is often associated with copper

[1]) J. H. Allaart (personal communication) has discovered near Brede Fjord and Igaliko Fjord a soda metasomatism affecting Julianehåb Granite and forming a number of areas up to over a hundred metres wide of medium- or coarse-grained syenitic rock. This rock lacks quartz and consists chiefly of albite which frequently shows chess-board structure and is often deformed.

Table II.

Relative development and time-sequence of mineral parageneses, Josvaminen:

(1) Main period of felspathization; syenitization of granitic rocks.
(2) Formation of pegmatite along fractures of first period of fracture:
(3) Main period of epidotization and related mineralization; nodules, fissure fillings and alteration round vugs and fractures formed in first period of fracture.
(4) Main period of Cu-ore deposition along major faults of second fracture-period.
(5) Joint and fissure fillings.



ore in other regions (e.g. Michigan, the Rhodesian Copper-belt — see Vaes, 1962) the connexion between the two phenomena is not invariably direct. The Josvaminen occurrences, however, can be treated as parts of one mineralization process, as will be seen, even though the latter may have covered a more extended time interval than is suggested by Table II.

Ore deposition mainly took place along major shear zones. Although its paragenesis overlaps that of epidotization in time (bornite, chalcocite, haematite are often associated with epidotization as late minerals, and epidote, garnet, actinolite, alkali felspar formed with the main ore bodies) it is chiefly later than epidotization for it formed under declining temperatures as will be discussed. Movement and mineralization alternated along the shear zones prior to ore deposition and, it is suggested, after the main period of epidotization, but the Cu-sulphides show no cataclastic effects and are younger than the movements.

Some mineralized joints and fissures containing copper and other minerals represent the last stages of mineralization.

VI. THE MINERALS IN AND ASSOCIATED WITH THE COPPER DEPOSITS

The minerals formed during or in association with the copper ore deposition at Josvaminen are listed below, noting their distribution and position in the paragenetic sequence (Table III).

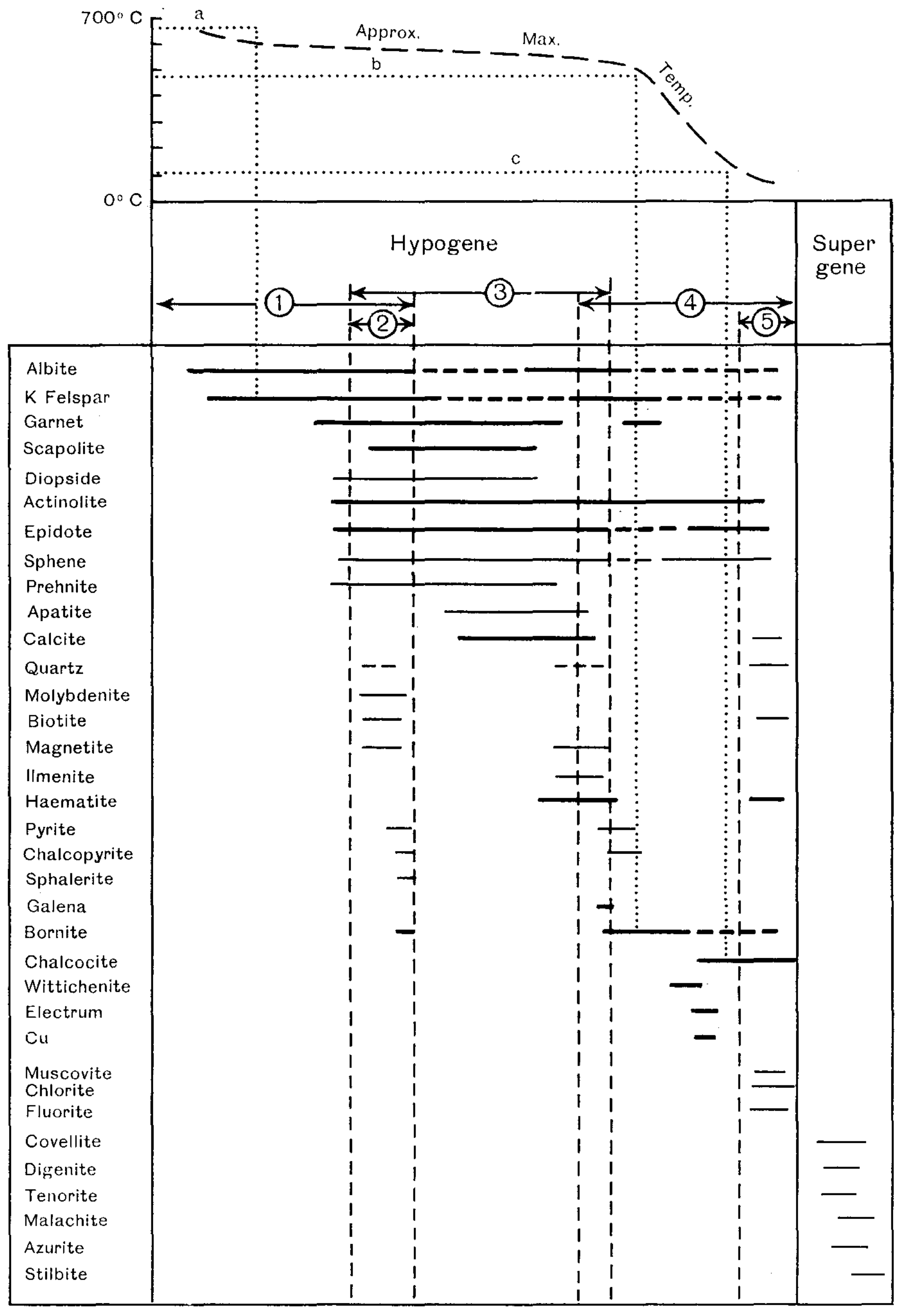
Alkali felspar. Albite and microcline are important in most pegmatite veinlets and occur in joint and fracture fillings. They are the main constituents of the felspathized granitic rocks and felsites and also formed during epidotization and copper-ore deposition. They thus occur at all stages in the mineralization.

Garnet. The garnet present is weakly birefringent and commonly shows the zoning and dodecahedral twinning characteristic of members of the grossularite-andradite series (WINCHELL 1951). Under the conditions believed to have obtained during its formation (see Section VII) a hydrogarnet might be expected from data given by PISTORIUS and KENNEDY (1960), though its refractive index is higher than that of the hydrogarnets described by HUTTON (1943) and of hibschite (PABST 1942) and falls within the refractive index range of the dry garnets of the grossularite-andradite series. But this evidence is inconclusive; especially since no account has yet been taken of the influence of andradite substitution in the hydrogrossularites. Garnet occurs (1) as a late mineral in felspathized rocks, (2) as fissure- and void-fillings in epidote veinlets and nests, (3) as an early mineral in the Josva copper vein. In the felsitic rocks fine-grained garnet forms irregular veinlets and aggregates. Skeletal garnet crystals with a kind of atoll texture are common, showing euhedral, often six-sided outlines and enclosing hexagonal to rounded single grains or aggregates of alkali felspar. Many skeletal crystals have grown outwardly as a series of zones around their felspar cores, but the last were generally gradually replaced during growth and a homogeneous garnet porphyroblast ultimately resulted. The zonal textures show that individual porphyroblasts can coalesce to form glomeroblasts. Garnet is absent from the massive quartz-bearing epidote nodules and streaks, but is abundant in quartz-poor epidote veinlets and nests where it occurs in void-fillings and occasionally in the surrounding epidotized rocks. It is often interstitial to scapolite; both minerals may be replaced by calcite and potash felspar. In the Josva vein garnet crystallized before most of the epidote and forms small euhedral crystals particularly associated with albite—it becomes scarce when albite is subordinate to potash felspar. In the paragenetic table garnet largely coincides with the main period of epidotization, but its occurrence in the Josva vein suggests a period of formation more extensive than that of scapolite and diopside which have not been found in the copper veins.

Table III.

Paragenetic sequence of minerals, Josvaminen.

Numerals within circles refer to stage numbers in Table II. Temperature reference points *a b c* are explained in Section VII (a).



Scapolite. Scapolite occurs mainly with garnet as void-fillings in epidote veinlets and nests. A few pegmatitic veinlets consist predominantly of scapolite, accompanied by garnet, prehnite, epidote, clinozoisite, sphene, calcite and albite. The scapolite may form coarse radial aggregates to which garnet is interstitial.

Diopside. In the altered granites diopside forms porphyroblasts and replaces hornblende. In felsitic rocks it occurs in streaky aggregates associated with relict hornblende and sometimes in idiomorphic aggregates together with garnet. It is also found as fissure fillings in epidote veinlets. In most cases diopside seems to have formed roughly at the same time as garnet and scapolite.

Actinolite. In the felsitic rocks actinolitic amphibole can occur as corroded and partly replaced relics, sometimes associated with biotite. Recrystallization of amphibole was undoubtedly important during mineralization and much of the actinolite in the mineralized rocks was presumably derived from wall rocks.

The amphibole in the Green Schists is usually pleochroic blue green to pale green. The later amphiboles have a pleochroism green or pale green to pale yellow-green and are often fibrous or highly prismatic in habit; they usually occur in streaks or (often radiating) aggregates.

The first abundant development of actinolite coincides with the main period of epidotization. The mineral often fills voids in epidotic veinlets, streaks and nests. Unlike garnet and scapolite it is also an important constituent of the massive epidotic nodules and streaks, especially those bearing quartz. The epidote and actinolite may form equigranular hypidiomorphic aggregates in which they presumably crystallized simultaneously. Actinolite is also abundant in the Josva vein, where it can form a fibrous groundmass cementing the fault breccia and is associated with epidote and alkali felspar in streaks within the fault breccia. Actinolite and its associates are in part strongly affected by para- and post-crystalline deformation, but in part are undeformed and apparently deposited after the last movements ceased. In this later stage actinolite often crystallized together with bornite and chalcocite in cracks and fissures. Actinolite apparently formed during the whole period of mineralization in the fault zone at Josvaminen.

Actinolite is also often found as later joint- and fracture-fillings: so its formation covers almost the whole period of mineralization. In the very latest stages it is replaced by chlorite.

Epidote minerals. Clinozoisite and zoisite occur locally in some of the felsitic veinlets and pegmatitic scapolite veinlets. However, the commonest epidote mineral is pistacite, which developed abundantly throughout almost the whole mineralization period but particularly during the main stage of epidotization when it formed replacement veinlets along fissures in the schists and felsitic and dyke rocks. A number of Ca-rich or Ca-bearing minerals, apatite and especially actinolite and garnet, are associated with the epidote at this stage as also are haematite and some magnetite. Although epidote mainly replaced schist it also fills voids and fissures where it is often later than the other void-filling minerals and may be found along cracks and cleavage planes in scapolite, garnet and actinolite.

In the Josva vein formation of pistacite mainly preceded deposition of Cu-sulphides, which are often interstitial to epidote aggregates. But rims of pistacite can surround lenticles of bornite and chalcocite, streaks of epidote may occasionally transect bornite lenticles, and epidote nests may be found as void-fillings in ore masses. Also actinolite and potash felspar may be earlier or later than the epidote. However, where garnet and alkali felspar are associated pistacite always appears later than those two minerals. Pistacite aggregates and euhedral crystals are frequently found as coatings on joints, and as joint-fillings, sometimes associated with late minerals such as chlorite and fluorite. Formation of epidote thus apparently lasted until the last stages of mineralization.

Sphene. In the Josva vein sphene forms reaction rims around ilmenite grains. Its main period of development apparently coincides with the main period of epidotization, however, for it is most common in epidotized rocks.

Prehnite. This mineral has been observed as radial aggregates in scapolite veinlets and as void-fillings in epidote veinlets, nests and streaks. It is mostly accompanied by other void-filling minerals such as garnet, scapolite and diopside, with which it is presumably roughly contemporaneous.

Apatite. Apatite is an accessory mineral in the Green Schists and other country rocks but is present in more than accessory amounts in some epidotic nodules; also it is rather frequent in the Josva vein.

Calcite. In the quartz-bearing epidote nodules and streaks west of Lilianminen, calcite is rather rare, but it is common in the epidotized rocks near Josvaminen and most abundant as void-fillings in epidote veinlets. It is found interstitial to and replacing garnet, scapolite, actinolite, and epidote. In the Josva vein calcite is an accessory constituent associated with actinolite or epidote. It occasionally occurs in open joints and fissures.

Quartz. Quartz can be an important constituents of veinlets traversing or surrounding epidote rock bodies. One euhedral quartz crystal has been found enclosed by a bornite lenticle in the Josva vein. Euhedral quartz crystals are rather common as encrustations in the mineralized joints.

Quartz is apparently only of local development; it formed mainly in pegmatites, at a few places during the later stages of epidotization, and, finally, in joints and fractures during the later stages of mineralization.

Magnetite. Euhedral magnetite crystals (about 2 mm in size) occur in the Green Schists and felsitic schists near the Josva vein. Appreciable amounts of magnetite are present in the pinkish-coloured felspathic margins of mineralization nests in the felsitic schists bordering the Josva vein. In the rocks of Josva vein magnetite is frequently corroded by felspar and epidote, the last often surrounding grains of magnetite. The magnetite lies mainly between felspar or epidote crystals and only rarely forms (corroded) inclusions in the bornite-chalcocite lenticles. Some quartzo-felspathic veinlets west of Lilianminen may also contain a little magnetite.

Magnetite crystallized before the sulphides, presumably mainly during the last stages of epidotization and the first stages of important copper ore deposition in the Josva vein.

Ilmenite. Magnetite-bearing rocks sometimes contain a few grains of ilmenite often surrounded by grains of sphene. The mineral is presumably contemporaneous with magnetite.

Haematite. Haematite, associated with quartz and felspar, occurs abundantly in veinlets traversing and surrounding the epidote nodules and streaks west of Lilianminen. It also is found as coarse-grained aggregates in the central parts of some epidote veinlets and nests. In the Josva vein it is an accessory con-

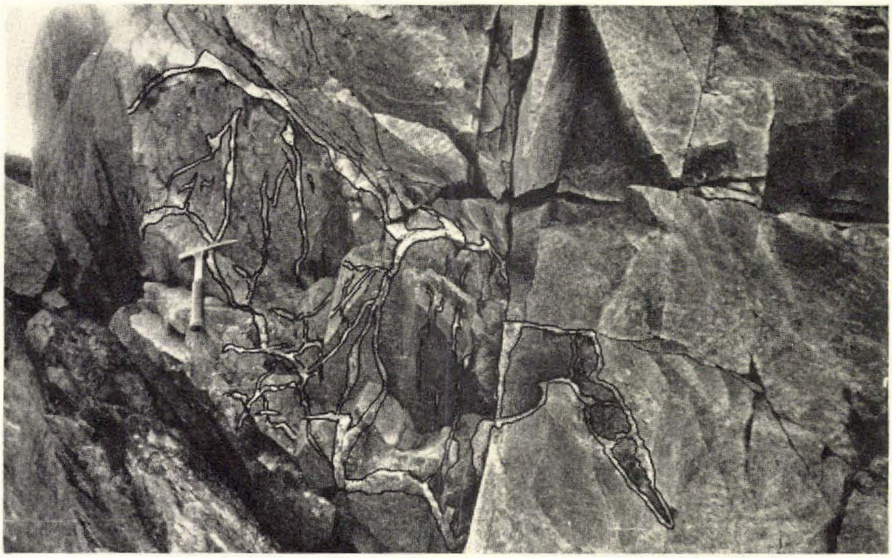


Fig. 19. An epidote nodule in the Green Schists near Lilianminen. The nodule is traversed and surrounded by veinlets consisting of coarse-grained alkali-felspar and haematite. G.G.U. Photo. O.I.S.

stituent, occurring mainly as corroded grains enclosed in the bornite-chalcocite lenticles. It has not been found in contact with magnetite or ilmenite.

Haematite is also a characteristic accessory of felspathized rocks of original granitic composition and is common in mineralized joints. Furthermore fault zones with reddish haematitic impregnations occur on the coast of Kobberminebugt, one east of Josvaminen, another about 1 km S.W. of Josvaminen. Haematite seems principally formed during the last stages of the main period of epidotization, but the fault impregnations suggest that there may have been another later period of haematitization.

Molybdenite. This mineral is very rare; it occurs scantily in some quartzo-felspathic pegmatitic veinlets.

Biotite. The earliest biotite related to the mineralization processes occurs in some quartzo-feldspathic veinlets. Later biotite replaces amphibole, mostly in rocks which also contain chlorite, muscovite, or fluorite.

Pyrite. Euhedral pyrite crystals are locally found in the Green Schists and granitic rocks, especially near centres of epidotization. The mineral is also present in some pegmatitic veinlets. Pyrite aggregates usually contain interstitial chalcopyrite grains.

Chalcopyrite. Chalcopyrite, often associated with some pyrite or bornite, occurs in the Green Schists, granitic country rocks, and pegmatitic veinlets. The accompanying bornite is always fine-grained and may contain numerous fine exsolution blades of chalcopyrite. The chalcopyrite and bornite grains show "mutual boundary" relations, suggesting contemporaneous formation. The following observations indicate the exsolution rather than replacement origin of the chalcopyrite blades in the bornite:

1) the bornite-chalcopyrite intergrowths may occur without accompanying grains of chalcopyrite,
2) when chalcopyrite grains occur with the intergrowths they appear earlier than, or contemporaneous with, the bornite,
3) the chalcopyrite blades may be restricted to the central parts of the bornite crystals.

Small bornite grains with exsolved chalcopyrite have occasionally been observed in the Josva vein, but the bornite in the vein is generally a later generation without exsolved chalcopyrite. Chalcopyrite grains have not been observed in the Josva vein.

Sphalerite. Has only been observed once. It occurs in a pegmatitic veinlet where it shows "mutual boundaries" against chalcopyrite.

Galena. Galena is associated with bornite-chalcopyrite intergrowths in small epidote veinlets in the Green Schists N.E. of Josvaminen, and is interstitial to epidote and other silicates. It occurs as corroded inclusions in the bornite; chalcopyrite blades in the bornite can broaden and spread out round the galena inclusions which are obviously earlier than the bornite and chalcopyrite.

Bornite. In the Green Schists N.E. of Josvaminen bornite forms disseminated grains and small aggregates in the network of epidote veinlets, always as a late mineral interstitial to the silicates or in the central parts of the veinlets. It can contain exsolution blades of chalcopyrite and may be associated with galena and chalcopyrite. Chalcocite is generally absent, but may occur in slight amounts. Bornite of this high-temperature habit may also occur in the gangue material of Josva vein and in some other smaller mineralized shear zones.

However, the bulk of the bornite in Josva vein occurs in lenticles and as impregnations in the fault breccia. This coarse-grained bornite (often attaining grain sizes of 1—2 cm) lacks chalcopyrite exsolution blades and is associated with important quantities of chalcocite, with which it frequently forms 'myrmekitic' intergrowths. As described before, bornite and actinolite were often deposited more or less contemporaneously in the same fractures or along the same shear planes. Epidote and alkali felspars mainly preceded the Cu-sulphides, but overlapping time relations are apparent. Magnetite, ilmenite and haematite are also earlier than the bornite. On the other hand, chlorite and fluorite may occur in cracks and voids in the bornite aggregates and are clearly later than the bornite.

Bornite is also found in mineralized open joints. Here it is most frequently accompanied by contemporaneous actinolite with which it may form orientated intergrowths, the actinolite needles being arranged according to the crystallographic directions of the enclosing bornite. Other associates of bornite in open joints are chalcocite, chlorite, fluorite, haematite, alkali felspars, and epidote.

The deposition of the bulk of the bornite in Josva vein took place during the main period of copper ore deposition (see Table III). However, some bornite, usually with exsolved chalcopyrite, is found in pegmatitic veinlets and precipitation of the mineral may have commenced as early as the main stage of pegmatite formation.

Chalcocite. Bluish-white chalcocite has weak anisotropy and pleochroism distinctly visible in oil. Etching with HNO_3 brings out the rhombohedral cleavage very clearly. The chalcocite forms inequigranular aggregates with grain size from about 0.5 cm to less than 0.1 mm. The coarser grains frequently show polysynthetic twinning lamellae and other lancet-shaped or more irregular-shaped lamellae, which suggest that they are paramorphs after hexagonal chalcocite, formed above 103° C (RAMDOHR 1960, p. 416). The finer-grained chalcocite does not show these lamellae; it is often developed in veinlets and rims replacing bornite along grain boundaries and cracks, and as interstitial masses between the silicates and bornite (Plate I, fig. 1, and Plate II, fig. 1). It is regarded as having crystallized directly from solutions at less than 103° C.

The hypogene nature of the chalcocite emerges from the following observations:

a) Part of the chalcocite paramorphs hexagonal chalcocite formed above 103° C.
b) The earlier bornite containing exsolution blades of chalcopyrite is accompanied by only minor amounts of chalcocite. If the chalcocite were of supergene origin it would attack both the earlier and later bornite equally.
c) The chalcocite is not widely dispersed, contrary to what might be expected of supergene chalcocite. It occurs with bornite in veinlets and nests. No bornite lenticle or mass more than 0.5 cm across has been completely replaced by chalcocite.

These facts suggest that the chalcocite crystallized later than bornite from residual solutions, in the same openings and alleys as the bornite. The distribution of wittichenite also shows a clear relation to the bornite-chalcocite boundaries. Supergene solutions could be expected to follow paths locally diverging from those taken by the fluids that deposited the bornite and occasional complete replacements of bornite masses would be likely.

The larger bornite lenticles in the Josva vein often bear thin rims of chalcocite. In the lenticles themselves chalcocite usually forms delicate intergranular veinlets and masses, which often reveal the coarse-grained nature of the bornite. Larger aggregates of chalcocite may enclose corroded relics of bornite. Myrmekitic intergrowths of bornite and chalcocite are very common. The voluminous literature on these intergrowths has been summarized by SCHNEIDERHÖHN (1920), GEIJER (1924) and, recently, RAMDOHR (1945, 1960), who reviews their possible origins. In the present case several more or less conclusive observations indicate the replacement origin of the intergrowths:

1) Replacement of bornite by chalcocite is clearly demonstrated by structures and textures. The intergrowths generally occur at the borders between replacing chalcocite and replaced bornite. The chalcocite of the intergrowth is continuous with chalcocite grains that have corroded and replaced the bornite (Plate II, fig. 1, and Plate III, fig. 2).
2) In some cases replacement of bornite apparently continued after the myrmekite formation, a few small rounded or worm-like inclusions of bornite in chalcocite being all that is left of the intergrowth (Plate I, figs. 1, 2).
3) Although, in some isolated intergrowths, chalcocite is seemingly not connected with grains replacing the bornite, it has usually clearly penetrated the bornite along its crystallographic directions (Plate I, fig. 2).
4) In the most common form of the intergrowths the chalcocite is more or less continuous, whereas the bornite forms isolated rounded or vermiform inclusions. Forms transitional between those described under points 2) and 4, or 3) and 4) can be occasionally observed (Plate I, fig. 1 and Plate II, fig. 2).
5) Not infrequently the intergrowths consist of three components: bornite, wittichenite, and chalcocite (Plate II, fig. 2 and Plate III, figs. 1, 2). Other

textural relations clearly show that wittichenite is also replaced by chalcocite (see below).

6) Bornite in the intergrowths sometimes contains exsolved blades of chalcopyrite which are also corroded and replaced by the chalcocite (Plate III, fig. 3). The replacement origin of the intergrowths is conclusively shown by these examples. Moreover, bornites containing an excess of $CuFeS_2$ cannot be expected to have formed contemporaneously with chalcocite (Ramdohr 1960, p. 456).

In Table II the crystallization period of chalcocite is indicated as directly following that of bornite.

Wittichenite. This mineral is a regular accessory in the bornite and chalcocite. Its colour in air as well as oil is creamy-yellow. It has a moderately high reflectivity and a weak reflection pleochroism when observed in oil. Anisotropic effects are rather pronounced in oil, but weak in air. The mineral is distinctly softer than bornite but is somewhat harder than (or about as hard as) chalcocite. Etching with HNO_3 (conc) gives a bluish stain, which may slowly turn brownish, KCN (20 %) gives weak brownish and bluish stains. HNO_3(2n), HCl (conc), NaOH (40 %), KOH (40 %), $FeCl_3$ (20 %), and $HgCl_2$ (5 %) give negative results. The identity of the mineral is proved by an X-ray powder diagram, which has been compared and found to agree very well with the data of wittichenite given by Nuffield (1947). Thanks are due to Mrs. M. Danø for the preparation and interpretation of the X-ray diagrams.

Wittichenite occurs as small rounded inclusions, usually less than 0.2 mm in diameter, dispersed in the bornite, and as somewhat larger and more numerous grains along the contacts of the bornite areas with gangue material or chalcocite. Wittichenite inclusions in chalcocite seem more or less corroded and have apparently been inherited from replaced bornite. Wittichenite grains in the bornite or chalcocite are often traversed by curved veinlets of chalcocite; these are perhaps shrinkage cracks which have become filled with chalcocite. Wittichenite and bornite frequently form myrmekitic intergrowths. It is unlikely that these intergrowths are due to replacement of wittichenite by bornite since the area occupied by an intergrowth is often larger than the largest grains or aggregates of wittichenite. Also there is no evidence of bornite being replaced by wittichenite; the latter usually occurs as rounded or embayed areas in the bornite and both minerals were presumably deposited at about the same time. Later chalcocite may join the bornite and wittichenite to form a composite myrmekite of all three minerals.

At very high temperatures, well above those at which the unmixing of chalcopyrite from bornite begins, wittichenite can apparently be taken into solid solution by bornite (Oen 1959). In the present case temperatures were apparently not so high. Wittichenite was not formed before the relatively low temperatures during the later stages of bornite deposition were reached. During the later stages of bornite deposition were reached. During its period of formation it frequently formed myrmekitic intergrowths with bornite. The formation of wittichenite seems to end roughly when bornite ceased crystallization; both minerals were then replaced by chalcocite. These relations suggest that the bornite-wittichenite myrmekitic intergrowths may have been formed by simultaneous deposition along an eutectic line. The textural evidence for this can be summarized as follows:

1) Textural relationships indicate roughly simultaneous deposition of bornite and wittichenite (see above). Replacement relations are lacking.

2) Wittichenite is related to the bornite-chalcocite boundaries in its distribution, i.e., most probably to the circulation paths of the ore solutions during or after the later stages of bornite formation (see under "chalcocite") (Plate II, fig. 2 and Plate III, figs. 1, 2).
3) Simultaneous cessation of the deposition of bornite and wittichenite is indicated by the simultaneous replacement of both minerals by chalcocite, which was deposited immediately after the bornite (Plate II, fig. 2 and Plate III, fig. 2) (see under "chalcocite").
4) Regular distribution of the wittichenite, which is nowhere in excess of the bornite: the proportion of wittichenite in the investigated samples from the Josva vein is more or less constant, as might be expected when deposition follows an eutectic line.

Electrum. A few small, rounded or irregularly shaped grains of native gold or electrum are occasionally observed as inclusions in bornite and chalcocite. Its place in the paragenetic sequence is difficult to determine and it is provisionally placed between bornite and chalcocite.

Native copper. Only one grain of native copper has been observed, a small irregular inclusion in bornite. In the paragenetic table it is provisionally placed between bornite and chalcocite.

Chlorite. Chlorite is apparently one of the latest minerals in the paragenetic sequence and often replaces actinolite. It is found in the altered granitic rocks, in voids in pegmatitic veinlets, in nests and streaks in the Josva vein where it is later than the ore, and in joint- and fracture-fillings.

Muscovite. Minor amounts of muscovite or sericite are sometimes found in association with chlorite. Small muscovite flakes and sericitic masses have often developed as alterations of felspar.

Fluorite. Pinkish fluorite is rather common as joint- and fracture fillings. The mineral also occurs in the altered granitic rocks and the Josva vein. It is always interstitial to the other minerals and is often accompanied by chlorite.

Covellite. Covellite is present both in its common modification, showing bright violet-blue and red-violet colours, and an its less common form, which shows only blue colours. The mineral has developed locally along grain boundaries and cracks in bornite and chalcocite, and is presumably of supergene origin.

Digenite. Thin veinlets of digenite may locally traverse bornite and chalcocite grains. Digenite is also found along grain boundaries of bornite and chalcocite, especially where they are altered to covellite and tenorite.

Tenorite. Tenorite is locally found as supergene alterations of bornite and chalcocite and is commonly associated with covellite.

Malachite and Azurite. These minerals occur as thin crusts on the Cu-sulphides and as crusts on joint walls and in cracks. They are more common in samples from the waste piles at the mines than in the solid exposures.

Stilbite. This mineral has not been found at Josvaminen by us, but according to Ball (1923, p. 32), it is at places found as a secondary mineral on malachite, and it occurs in mineralized schists west of Rinks Havn.

VII. PHYSICO-CHEMICAL CONDITIONS OF MINERALIZATION

Tables II and III summarize the successive stages of mineralization, each of which is characterized by the predominance of a certain paragenesis of minerals. The explanation of this paragenetic sequence is to be sought in changing temperature, pressure, and state and composition of the mineralizing fluids.

(a) Temperatures of mineralization.

During the whole period of felspar formation albite and potash felspar crystallized together. According to experimental evidence this only happens below 660° C (Tuttle and Bowen 1958, pp. 42–43). It may be regarded as giving an upper limit to the temperatures throughout mineralization.

Another reference point is provided by the temperature at which chalcopyrite begins to exsolve from bornite (475° C) (Schwartz 1931, p. 186). This may be regarded as the minimum temperature at the beginning of the main period of copper ore deposition.

All the minerals deposited during the main periods of felspathization and epidotization (Table III) may form in the interval between 660° C and 475° C (*a* and *b* on Table III); so it seems reasonable to assume that this roughly covers the main periods of felspathization and epidotization.

A third point on the temperature scale of Table III is given by the inversion of hexagonal and rhombic chalcocite at 103° C (Ramdohr 1960, p. 416). Deposition of the Cu-sulphides commenced at about 500° C and finished at well below 103° C. The rapid decrease in ore with depth, the structures and textures of the ore veins, the very constant and close association of bornite and low-temperature chalcocite in the same restricted spaces, all indicate relatively rapid precipitation and cooling as compared with the earlier felspathization and epidotization, which involved more widespread replacements of pre-existing rocks.

(b) Pressure conditions during mineralization.

(i) Load pressure.

The rapid decrease in ore with depth, the low temperatures rapidly attained at the end of hypogene mineralization, and mineralization filling fissures, vugs, and open joints, indicate that the ores at Josvaminen were formed at comparatively shallow depth. Quantitative estimates are hard to make but are desirable for an appraisal of the other physical variables and the genetic classification of the deposit. The present relief variation on Alángorssuaq amounts to 660 m, and 1000 m does not seem an excessive estimate of the thickness of rock removed by erosion since mineralization. Assuming that temperatures at the end of the hypogene mineralization (indicated by low-chalcocite deposited below 103° C) approached those which would be due to the normal geothermal gradient (30°/km), we may suggest about 3 km as the maximum depth under which ore-deposition took place. Depths of about 1 to 3 km correspond to load pressures ranging from about 300 to 900 bars.

(ii) Stress Pressure.

Shearing stress was important during felspathization of the granitic rocks, and fracture preceded the main period of epidotization. The main periods of epidotization and copper ore deposition were, however, not accompanied by shearing stress.

(iii) Evidence of high fluid pressures during epidotization.

Fluid pressures are hard to assess but some information can be gained from experimental results. According to Fyfe, Turner and Verhoogen (1958, pp. 149, 160) scapolite does not form readily in low-pressure experiments; this and its occurrence at higher metamorphic grades suggests a high pressure of formation. Diagrams of the hypothetical stability relations of scapolite show that at moderate to high temperatures the pair scapolite-calcite represents higher partial pressures of carbon dioxide than the pair anorthite-calcite. The same authors report that between 400° and 700° C at water pressures of 500 bars anorthite and calcite crystallize simultaneously instead of scapolite.

Data by Pistorius and Kennedy (1960) suggest that under high pressures hydrogrossularite and quartz or grossularite and quartz are stable relative to the pair anorthite-wollastonite. If silica is deficient, however, grossularite may be stable at lower pressures. Thus, although garnet need not indicate high pressures, its formation should theoretically be favoured by such pressures (Yoder 1950, p. 248; Fyfe, Turner and Verhoogen 1958, p. 156).

Fyfe, Turner and Verhoogen (1958, pp. 170—171) have summarized the data concerning epidote and prehnite. It appears that in the laboratory these minerals will form rapidly at low temperatures only at pressures well above 3000 bars. Prehnite glasses invariably tend to yield anorthite-wollastonite at low pressures (400 bars) and 350°—700° C, whereas in the presence of prehnite seeds, at 3000 bars water pressure, the same glasses become rapidly converted to prehnite around 350° C. Crystallization of epidote in low-grade metamorphic rocks might be influenced by coupled reactions, e.g., in a reaction yielding chlorite epidote may form at relatively low pressures. The formation of the epidote-rock bodies near Josvaminen apparently did not involve coupled reactions of this kind, however.

It appears then that a number of minerals connected with the epidotization are suggestive of high pressures. At the same temperatures as, but lower pressures than those during epidotization anorthite-wollastonite or anorthite-calcite are believed to be stable relative to scapolite-calcite, grossularite and prehnite. The data cited, scanty as they may be, indicate that epidotization took place under pressures far in excess of the estimated load pressures, so that high fluid pressures may be inferred.

(iv) The influence of high vapour pressures on epidotization and associated mineralizations.

The epidotic replacements developed along fissures, cracks and vugs into which hydrous fluids could enter under high vapour pressures. Other factors could also generate high vapour pressures during crystallization within the pores and fractures. The replacement by epidote of chlorite and amphibole in the Green Schists liberated water and if reaction rates were fast and the rocks had low permeability this might cause a rise in water pressure. Furthermore vapour pressures might rise during crystallization in certain systems through the "second boiling point" phenomenon (Turner and Verhoogen 1951, pp. 317—331).

Field observations indicate that the epidote nodules, streaks and veins replaced pre-existing rocks in the absence of contemporaneous deformation. They presumably formed at constant total volume and, as already deduced (p. 60), at fairly constant temperatures. Turner and Verhoogen (1951, pp. 36—37) have shown that under these conditions the effects of increasing pressures on the chemical potentials of the reacting components and their products may gradually decrease the affinity of a reaction so that it eventually stops. In our case, rise in partial vapour pressure of water may have eventually stopped the reaction by which epidote is produced from chlorite or amphibole with the liberation of water, so that the epidotic nodules, streaks and veinlets ceased growth. During these later stages, the liberation of hydroxyl-groups may also have led to a relative rise of the oxygen partial pressures, which in turn may have favoured the abundant development of haematite in rims around epidote nodules (see also p. 68). In addition, as will be discussed later, epidotization was limited by the relatively low Ca-content of the mineralizing fluids.

Account should also be taken of the steep temperature and pressure gradients that would arise along the openings. Since the fluids entering these spaces were presumably hotter than their country rocks, temperatures, like the fluid pressure, would be at a maximum in the pore-spaces and fissures, decreasing outwards in the wall rocks.

These pressure and temperature gradients may, in part, have caused the variations in mineralogical composition within the epidotic replacement bodies. The chemical (topomineralic) effects of the wall rocks will be discussed later: here the following inferences may be drawn:

1) Since epidote is concentrated as replacements in the wall rocks it would seem to have formed at somewhat lower temperatures and total fluid pressures than the minerals in the central parts of the veinlets (compare Firman 1957, p. 218). The partial pressures of water may have gradually increased through epidotization of chlorite and amphibole, however, and may eventually have become greater in the zone of epidotization than in the central parts of the veinlets.

2) The concentration of garnet, scapolite, calcite, actinolite, diopside and prehnite in the central parts of veinlets suggests that these minerals formed at somewhat higher temperatures and fluid pressures than the epidote. The diversity of the mineral combinations in the central parts of the different veinlets and vugs may be accounted for by variations in partial vapour pressures of the different components. The common assemblage garnet-scapolite-calcite presumably formed under relatively high partial pressures of CO_2, whereas the formation of actinolite, diopside and prehnite may have been favoured by lower ratios of P_{CO_2}/P_{H_2O}.

(v) Fluid pressure during copper ore deposition.

The main period of copper ore deposition, like that of epidotization, was preceded by fracture and shear. As abundant copper ore was formed only along major faults under rapidly falling temperatures, suggesting contamination by meteoric waters (see Section VIII), fluid pressures would be comparatively low during its deposition. In joints and smaller fractures not connected with the surface, however, high fluid pressures may have persisted and osmosis may have been important. Volatiles may reduce considerably the water pressures at which epidote will form, perhaps explaining its development in joints and fissures (FYFE, TURNER and VERHOOGEN 1958 pp. 125—126), and temporary osmotic conditions may have caused local formation of epidote and garnet in the main bornite-chalcocite veins.

(c) Nature and composition of the mineralizing fluids.

It has been assumed that the mineralizing agents were hydrous fluids, the most efficient means of transporting large amounts of material in solution over considerable distances. At the high temperatures and pressures prevalent during the earlier periods of mineralization water must have been in the supercritical state and, as fluid pressures were considerably higher than load pressures, vapour phases would readily arise. The mineralizing agents were apparently pneumatolytic in the earlier and intermediate periods of mineralization; on cooling and reduction in pressure during the later period of ore deposition they became hydrothermal.

A high alkali and low silica content characterizes the imported fluids in all stages of the mineralization.

1. The fluids that felspathized the granitic rocks were clearly poor in silica. So too were the epidotizing fluids as may be inferred from the occurrence of prehnite instead of laumontite (FYFE, TURNER and VERHOOGEN 1958, p. 171) and the lack of quartz in certain epidotic nodules and veins. During the main period of copper ore deposition quartz was not formed.
2. The fluids that felspathized the granitic rocks were obviously rich in alkalis, particularly soda. Although during subsequent phases of mineralization deposition of alkali felspar was often superseded by that of other minerals (e.g. epidote) it continued intermittently and the fluids must have maintained their alkali content. Also, the formation of scapolite suggests a soda-rich environment.

Assuming that in other respects as well the imported fluids were of similar composition throughout mineralization, variations in mineral parageneses can be explained as follows.

Felspathization of granitic rocks took place in an open system with free migration of material (probably facilitated by the penetrative deformation that accompanied it) for reaction often went to completion. With waning movement towards the end of the episode decrease in permeability inhibited migration of material and lead to rise in vapour pressure and enrichment of the fluids in Mg, Fe, Ca, Si, through reaction with country rocks. Consequently the high-pressure minerals garnet, epidote, scapolite would tend to form instead of alkali felspar but would be strictly limited in development by the comparatively small amount of Ca, Mg, Fe, Si available in the fluids, thus explaining the merely incipient replacement of alkali felspar by garnet and epidote in the felspathized granitic rocks. This replacement would have been more thorough if it had been due to a fundamental change in the chemical composition of the imported fluids.

Pronounced epidotization arose only near fissures and vugs in Green Schists under static conditions (Figs. 14, 15 and 16). The veins and nodules clearly display the topomineralic effects of the wall-rocks in compositional gradients tabulated below.

central parts of veinlets; often open space fillings	scapolite calcite garnet prehnite actinolite diopside
replacements in wall rocks adjacent to veins; epidote nodules and streaks	epidote actinolite sphene apatite
outer rims around epidote nodules and streaks; later replacements in epidotized rocks and central fillings; later veinlets crossing epidote nodules and streaks	alkali felspars haematite magnetite quartz (locally)

The minerals from the central parts of the veinlets are relatively rich in Ca; those in the replaced wall rocks are less so and they contain, for example, higher ratios of (Fe, Mg) O/CaO (in actinolite) or $(Al, Fe)_2 O_3/CaO$ (in epidote) in sympathy with the chemical composition of the schists; finally those in rims around epidotic rock bodies and in late veinlets are poor in or devoid of lime, but rich in alkalies, iron and silicon. The outer replacement zone around the fissures and vugs is apparently impoverished in lime as compared with the surrounding amphibole-bearing schists and it is concluded that the mineralizing fluids were poor in lime and that the materials composing the calcic minerals were largely taken from the schists. There is no need to assume introduction of large amounts of lime from extraneous sources and part, if not all of the Ti and P required for sphene and apatite was probably also provided by the schists. The abundance and mode of occurrence of haematite, however, suggests that the fluids were comparitively rich in iron.

The minerals formed in the wall rocks of the copper veins during the main period of copper ore formation are essentially the same as those formed in the preceding periods and are mainly alkali felspars and actinolite with local garnet and epidote. The composition of the fluids apparently remained much the same as in preceding periods.

To summarize, the fluids which caused the Josva mineralization had the following properties:

1. high alkali content,
2. low silica content,
3. low Ca, Mg, Fe, Al content,
4. high ratio of iron to calcium,
5. high content of volatiles (CO_2, F, Cl, S_2, P_2O_5).

VIII. THE GENESIS OF THE COPPER DEPOSITS AT JOSVAMINEN

At Josvaminen hypogene pneumatolytic-hydrothermal fluids poor in silica, rich in alkalis and volatiles (CO_2, Cl, F, S_2, P_2O_5) reacted with country rock to gain Ca, Mg, Fe, Si, Ti and probably Al. Copper also was probably abstracted from the Green Schists for these include many metamorphosed basic igneous rocks and such rocks elsewhere in the world often contain significant quantities of copper which may well be original (see LINDGREN 1933 p. 517). Minor copper concentrations in South Greenland are characteristic of the Ketilidian Green Schists.

Temperatures during mineralization ranged from about 600° to less than 100° C. Load pressures probably corresponded to depths of 1 to 3 km. Fluid pressures were apparently rather high prior to major copper sulphide deposition.

Mineralization covered an extensive time period and commenced with a felspathization (syenitization) of granitic rocks accompanied by penetrative deformation promoting free migration of material. With cessation of movement reduced permeability inhibited free migration, and the fluid pressures and content of lime (liberated by alkali metasomatism) of the fluids rose, favouring formation of garnet, scapolite, prehnite and epidote. The available lime was soon exhausted, however, and replacement of alkali felspar by one or other of the above minerals was halted rapidly after inception in the rocks of granitic parentage.

Following this episode the Green Schists developed more or less isolated fissures and vugs which became filled with fluids under high pressure. Temperature and pressure gradients falling outwards from the voids instituted a fissure metasomatism (KORZHINSKY 1950, FIRMAN 1957). Lime and other elements migrated towards the voids where Ca-minerals favoured by high pressures, such as garnet, scapolite, prehnite and calcite, crystallized, though at lower partial pressures of CO_2 actinolite or diopside sometimes formed instead. Simultaneously, the cooler wall-rocks rich in (Mg, Fe)O and (Al, $Fe)_2O_3$, were replaced by epidote or epidote and actinolite at lower pressures.

The formation of abundant haematite at this stage indicates a temporary excess of iron in the fluids and comparatively high oxygen partial pressures, perhaps resulting from epidotization of chloritic and amphibolitic schists. Haematite crystallization lowered the Po_2/Ps_2 and Fe/Cu ratios in the fluids thus fitting them for the next stage, that of abundant bornite and chalcocite deposition.

The fissure metasomatism forming calcic minerals and governed by high fluid pressures and osmosis was only temporary: felspathization resumed as soon as fluid pressures or the lime content of the fluids fell, or the partial vapour pressure of water rose high enough to halt the amphibole- or chlorite-epidote reaction.

The main period of copper ore formation was preceded by movement along major faults which may have become connected with the surface. Three points are significant:

1. Important copper concentrations occur only along major faults.
2. The copper ore decreases rapidly with depth.
3. Copper sulphide deposition was accompanied by a rapid fall in temperature from about 500° C to below 100° C.

These relations may be explained by contamination of the hypogene fluids by meteoric waters. Steep pressure and temperature gradients along the faults may have caused ore components to migrate and be rapidly deposited there. That the copper did not come from surface waters is suggested by the association of accessory copper minerals with felspathization, pegmatites, and epidotization. Copper and other metals (Pb, Zn, Bi, Au, Ag) as well as S, F, were presumably concentrated in the copper-ore stage through abstraction of other elements by silicates during preceding stages of the mineralization. Iron, initially in excess, formed haematite. The sequence epidote-haematite-bornite-chalcocite (which typifies a group of topomineralic reaction deposits in green schists, see below and SCHERBINA 1941, p. 414) may have depended on total fluid pressures and the partial vapour pressures of the different components. Formation of bornite and chalcocite instead of, for instance, chalcopyrite, may be a consequence of the exhaustion of iron during the preceding stage of epidote and haematite formation. The formation of haematite is favoured by relatively high oxygen partial pressures (SCHERBINA 1941; FLASCHEN and OSBORN 1957; HOLLAND 1959). It is conceivable that the reaction amphibole- or chlorite-epidote which involves the liberation of (OH)-groups may under certain circumstances (constant total volume) lead to a rise in Po_2 relative to P_{H_2O}, Ps_2, etc., so that haematite will be stabilized. In this respect the concentrations of haematite around epidote nodules have much significance.

Important copper deposition did not take place on minor faults, joints and fractures; these usually bear the minerals characterizing the main period of epidotization, together with variable amounts of alkali felspar, quartz, chlorite, fluorite, bornite and chalcocite, all of which appear later than the epidote and its associates. The joints and minor faults, unlike the major faults, may thus have been isolated fractures during the main period of ore formation and the conditions of mineral formation in them were presumably more like those in the epidote veins rather than those in the ore veins. Supergene enrichment at Josvaminen is negligible.

Fluids like those responsible for the mineralization at Josvaminen might evolve from syenitic magma. During Gardar times S. Greenland was an alkaline magmatic province and the mineralization may be connected with this intrusive activity. The Nunarssuit complex which lies a few kilometres south of Josvaminen is largely augite syenite and includes pegmatites in many ways resembling those bearing copper minerals mentioned in Section V. The depth and steep temperature gradient under which the Josva deposits were formed suggest their derivation from a nearby shallow intrusion rather than other sources, and if, as is probable, the mineralized younger dykes at Josvaminen are Gardar they would further suggest a connexion with the Nunarssuit complex. Moreover, the important Gardar N.N.E. dextral tear fault crossing central Alángorssuaq is strongly impregnated with haematite where it crops out on the shores of Kobberminebugt (see Table I for spectrographic analysis) and if this haematitization is associated with the Josva mineralization the latter may well be Gardar in age.

On the other hand mineral parageneses like those in the early felspathization and epidotization stages at Josvaminen may pre-date Gardar dykes in E. Alángorssuaq and, as remarked in Section V, it is feasible that mineralization of similar type may have taken place more than once during the complex pre-Cambrian history of the region.

Minor copper concentrations (pyrite-chalcopyrite associations and malachite coatings) are common in the Green Schists but not the other rocks of S. Greenland. They are particularly abundant near Ketilidian migmatites (personal communication, A. Berthelsen). The copper mineralizations in Alángorssuaq agree in their distribution with this general observation. It is not unlikely that throughout the region copper expelled from Green Schists undergoing Ketilidian granitization was concentrated at the margins of migmatite areas. Further concentrations might have arisen in Sanerutian times. There is therefore a possibility that the ores at Josvaminen may be pre-Gardar deposits reworked and redistributed by later hypogene fluids.

Genetic classification.

The Cu-deposits of Josvaminen may be classified as mesothermal (Lindgren 1933, p. 529; Schneiderhöhn 1949, p. 22) if depth of formation is taken as a criterion, but their temperatures of formation were higher than those usually assumed for mesothermal deposits. The earlier and intermediate stages of mineralization clearly show pneumatolytic affiliations.

SCHNEIDERHÖHN (1941, pp. 55—57) has recognized a group of topomineralic reaction deposits, in which the mineral parageneses are chiefly determined by the composition of the wall rocks. The chloritic and epidotic Cu-ores in dolomitic sediments and basic rocks as well as their metamorphosed equivalents (green schists, amphibolites) belong to this group as do the pneumatolytic-hydrothermal deposits of, for instance, the Engels mine and other copper mines in Plumas County, California, and Ookiep in Klein-Namaqualand, South Africa (SCHNEIDERHÖHN 1941, pp. 193—195). Hydrothermal representatives include the Kupferberg in Silesia, the Foothill copper belt in California, a number of copper deposits in British Columbia, Arghana Maden in Turkey, and Messina in Transvaal (SCHNEIDERHÖHN 1941, pp. 442—450). The gold-copper deposits of Glava (SCHERBINA 1941) and some other small bornite deposits in Sweden (GEIJER 1924) apparently also are topomineralic reaction deposits.

From its field occurrence, mineral paragenesis, and conditions of formation the Josva copper deposit can be classified as a pneumatolytic-hydrothermal member of the group of topomineralic copper deposits in green schists.

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PLATES

Plate I.

Fig. 1. Replacement of bornite (grey) by chalcocite (white) has proceeded along grain boundaries in the bornite aggregates and along bornite-actinolite boundaries. Euhedral crystals of actinolite (black) show typical lozenge-shaped cross-sections. Somewhat to the right of the centre of the figure an apparently incipient stage in the development of myrmekitic texture is shown by the occurrence of a number of irregularly shaped replacement relics of bornite enclosed in chalcocite. The myrmekitic intergrowth above the centre of the figure shows a reduced amount of bornite suggesting that the myrmekitic textures represent an intermediary stage in the process of replacement of bornite by chalcocite. (51 ×)

Fig. 2. Chalcocite (white) has replaced bornite (grey) along grain boundaries, cracks, and crystallographic directions. The myrmekitic intergrowth at the upper right hand side of the figure shows an apparent crystallographic control displayed by the parallelly oriented bornite lamellae. Somewhat to the left, in the same bornite crystal, is another myrmekitic intergrowth, whose external form clearly shows the influence of the crystallographic directions in the bornite. Note the relative proportions of bornite and chalcocite in the two intergrowths; the intergrowth at the left apparently represents a more advanced stage in the replacement of bornite than the one at the right. (51 ×)

Fig. 3. Replacement of bornite (grey) by chalcocite (white) with incipient development of myrmekitic textures. The development of a number of small, isolated chalcocite drops in the bornite is thought to represent the first stage in the formation of chalcocite-bornite myrmekitic intergrowths; the next step is believed to consist of the enlargement and coalescence of the drops to form larger, continuous areas of chalcocite enclosing replacement relics of bornite. (102 ×)

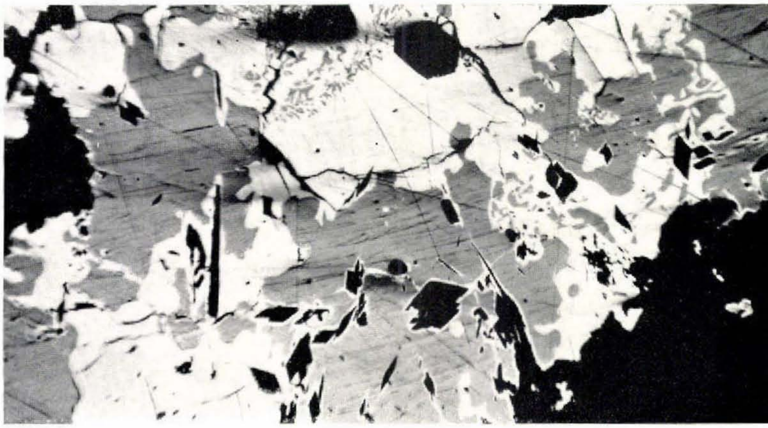

Fig. 1.

Fig. 2.

Fig. 3.

Plate II.

Fig. 1. Bornite (dark grey) is replaced by chalcocite (greyish white). The myrmekitic intergrowths have apparently formed as a result of incomplete replacement of bornite by chalcocite. Note the chalcocite drops and veinlet in the bornite to the right of the centre of the figure; this texture is believed to indicate an incipient stage in the replacement of bornite by chalcocite. (102 ×)

Fig. 2. Myrmekitic intergrowths of bornite (dark grey), chalcocite (greyish white), and wittichenite (white). The wittichenite occurred originally as granular inclusions in the bornite and in bornite-wittichenite myrmekitic intergrowths usually localized along grain boundaries in bornite aggregates (the grain boundaries of the bornite are not visible in the figure). Replacement of bornite by chalcocite has also proceeded mainly along the grain boundaries of the bornite. The formation of bornite-wittichenite myrmekitic intergrowths and of similar intergrowths of chalcocite and bornite are localized along the same grain boundaries and this has at places given rise to composite myrmekitic intergrowths of bornite, chalcocite, and wittichenite. (51 ×)

Fig. 1.

Fig. 2.

Plate III.

Fig. 1. Bornite (dark grey)—wittichenite (white)—chalcocite (white) relationships. The wittichenite grains (marked "w") show irregular cracks along which selective replacement by darker blue, secondary chalcocite has taken place. Wittichenite occurred originally as inclusions in bornite and along grain boundaries in bornite aggregates, sometimes forming bornite-wittichenite myrmekitic intergrowths. The chalcocite has replaced the bornite along grain boundaries and crystallographic directions. The development of chalcocite drops in the bornite has eventually lead to the formation of a myrmekitic texture. (102 ×)

Fig. 2. A typically developed bornite-chalcocite myrmekitic intergrowth in the ores of Josvaminen. Bornite is dark grey, chalcocite greyish white, and wittichenits white. The bornite-chalcocite myrmekitic intergrowth occurs in association with chalcocite grains replacing the bornite. Note that the proportions of the bornite component vary from place to place within the intergrowth. Locally the wittichenite has also formed myrmekitic intergrowths with bornite. (51 ×)

Fig. 3. Replacement of bornite (grey) by chalcocite (white) has proceeded from the grain boundaries of the bornite inward. The myrmekitic intergrowths have apparently resulted from this replacement and the textures still indicate the controlling influence exerted by the crystallographic directions in the bornite. Note the small blades of chalcopyrite (white) occurring along crystallographic directions in the bornite. Actinolite and epidote appear black on the photograph. (140 ×)

Fig. 1.

Fig. 2.

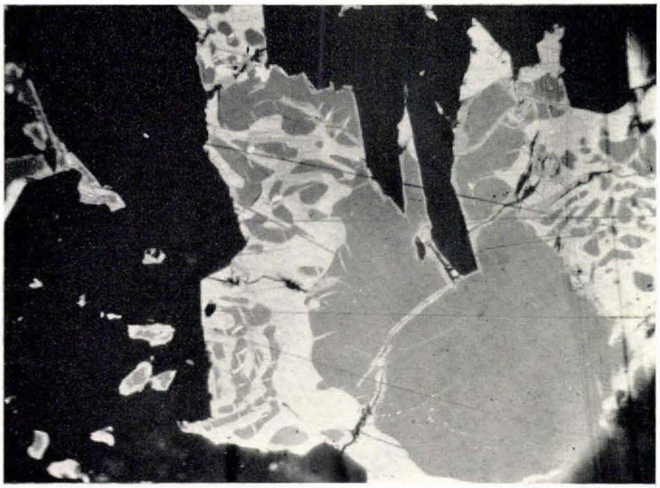

Fig. 3.