

SVERIGES GEOLOGISKA UNDERSÖKNING

SER. C.

Avhandlingar och uppsatser.

N:o 521.

ÅRSBOK 45 (1951) N:o 2.

LIME METASOMATISM AND
METAMORPHIC DIFFERENTIATION
IN THE ADAK AREA

BY

SVEN GAVELIN

Pris 3.50 kronor

STOCKHOLM 1952

KUNGL. BOKTRYCKERIET. P. A. NORSTEDT & SÖNER

513386

SVERIGES GEOLOGISKA UNDERSÖKNING

SER. C.

Avhandlingar och uppsatser.

N:o 521.

ÅRSBOK 45 (1951) N:o 2.

LIME METASOMATISM AND
METAMORPHIC DIFFERENTIATION
IN THE ADAK AREA

BY

SVEN GAVELIN

STOCKHOLM 1952

KUNGL. BOKTRYCKERIET. P. A. NORSTEDT & SÖNER

513386

Contents.

Introduction	3
The mutual relations between the »quartzites», the lime-silicate rocks (»skarn»), and the sulphide ores	4
Description of the »secondary quartzites»	7
Minerals	7
Mineral associations of the »ore quartzites»	11
Mutual relations of the different quartzites	16
Lime-silicate (»skarn») rocks	18
Survey of the lime-silicate rocks, their mineralogy and mutual relationship	18
Survey of the mineralogical and chemical changes during the skarn formation	28
Comparisons and some petrogenetical consequences	42
Bibliography	51

Introduction.

The Adak Area is situated in the north-western part of the Skellefte District in Northern Sweden. A geological map of the area, accompanied by a description of the principal rocks has recently been published, and in this paper the sulphide ores and the alteration of their surrounding rocks as related to the sulphide-mineralization have been briefly treated (16). In the present paper it is the author's intention to give a more detailed description of the mineralization processes in the silicate rocks acting in connection with the formation of sulphide ores, which, particularly in the Adak Mine, lead to formation of lime-silicates. The phenomenon was discussed in a preliminary way as a lecture before the Swedish Mineralogical Society in 1942, however publication of the results was deferred pending further information from the mining of the ores. Broadly speaking, the new data obtained only confirm the previously gained picture of the processes. By means of chemical analyses of lime-silicate rocks and the quartziferous altered rocks, the chemical variations can now be elucidated by numerical values. With regard to the optical constants presented for certain minerals in the present description, the following may be mentioned.

Determinations of the refractive index of minerals were performed in Na-light. In some cases the determinations have been made on powder, the values then being given as α_1 , γ_1 respectively. Where α or γ are supplied, the constants refer to crystals in which the orientation has been controlled by means of the U-stage. For the determination of the refringence of an almandite crystal I am indebted to Professor Gunnar Pehrman of Åbo University.

Other optical constants were determined with the aid of the U-stage using Na-light as the illuminating agent.

The mutual relations between the »quartzites», the lime-silicate (= skarn) rocks¹ and the sulphide ores.

The main structure of the Adak Area is that of a cupola, the different beds of volcanites and sediments dipping flatly away from the centre (16). The ore-bearing area is localized in the central part of the cupola, which is mainly built up of massive »secondary quartzites». Sporadic occurrences of layered rock-sequences within the quartzites show that the bedding is very flat, this being also the case in the inner parts of the cupola. The massive rocks have been designated as cordierite-quartzites and andalusite-quartzites and are interpreted as having been formed through a metasomatic alteration in connection with the sulphide mineralization of acid, or possibly intermediate volcanites. This interpretation is based on analogies with the well-known areas of Orijärvi and Falun (10, 18).

The principle ore-minerals at the Adak Mine are chalcopyrite and pyrrhotite. Minor constituents are arsenopyrite, pyrite and sphalerite. The sulphides appear as disseminations or as veinlets and veins of varying size, which brecciate the massive rocks in an irregular manner. On the whole the distribution of the sulphides is controlled by systems of fractures and fissures transversing the »quartzites». On that account, the individual ore bodies generally have very irregular contours. They appear mainly as elongated bodies with approximately horizontal axes and with very irregular cross-sectional outlines, their shapes varying considerably from one cross-section to another (see Fig. 1).

Several observations from the mines have revealed the deposition of the sulphides to be later than the formation of the »secondary quartzites». Often, but not always, the invasion of sulphides is intimately connected with the formation of lime-silicates on a comparatively large scale. Lime-silicates thus occur most often as very regular reaction zones between sulphide veinlets and quartzite. However, similar lime-silicate masses can also appear separately without any directly perceivable association with sulphides. In such cases the veins of lime-silicates are found to be controlled by the same systems of fractures in the quartzites as are the sulphide veins, and the lime-silicate veins often cut the bedding where present. The formation of lime-silicate rocks means, as will be shown in detail later, that lime enters the quartzites and reacts with iron, magnesia and silica. The introduction of lime into the quartzites is therefore a result of, firstly a supply in open fractures and secondly a diffusion from these fractures out into the surroundings. When the lime-bearing fractures are frequent and when the rate of diffusion from these fractures has been considerable, the separate lime-silicate veins may coalesce to form large, compact, lime-silicate masses.

The relation between the distribution of the lime-silicate rocks and the sulphide ore bodies is shown in general in fig. 1. The heavy lines in the block

¹ In this interpretation »skarn» and »lime-silicate rock» are used as synonyms.

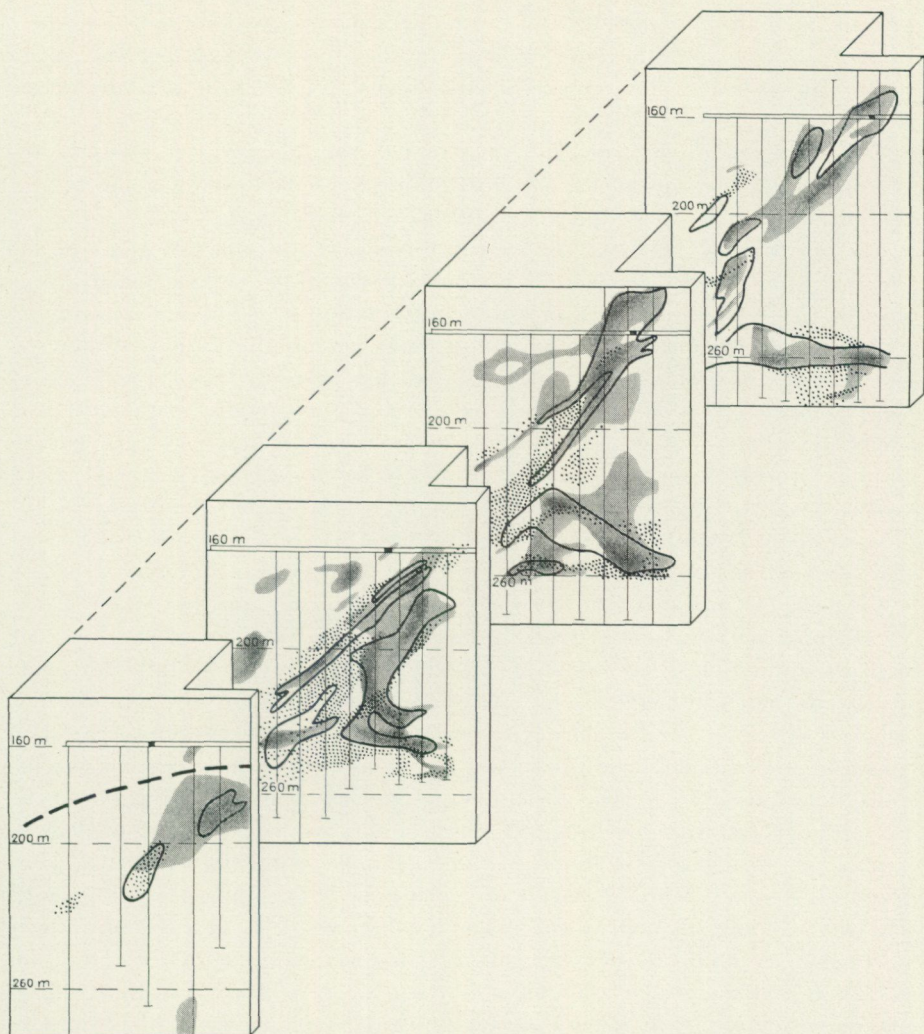


Fig. 1. Distribution of copper ores, skarn and garnet-bearing rocks within the deeper portions of the Adak Mine. Heavy unbroken lines indicate the boundaries of the ore-bodies. The heavy broken line indicates the stratification. Different shades indicate varying degrees of skarn mineralization. The frequency of garnet in the rocks is designated by dots in various densities.

diagram mark the boundaries of the ore bodies proper in the lower part of the Adak Mine. The frequency of lime-silicates has been denoted by shading, the heaviest shade representing almost pure lime-silicate rocks and the lightest, more sparsely occurring lime-silicate veins. (The gradation of the frequency of lime-silicates is based on the results from vertical drill-holes, appearing at a distance of 10 m from each other in the sections which represent the vertical faces of the blocks in fig. 1.) From fig. 1 it can be seen that the lime-silicates do not extend along the flat bedding of the cupola (denoted by the heavy

broken line). Instead there is an obvious agreement between the distribution of the sulphides and the lime-silicates. In their present position, the skarn rocks can therefore not represent calcareous layers in a stratified rock sequence.

The variations in the frequency of garnet in the quartzites is indicated by the density of the dots in the block-diagram. As is illustrated by the figure, the garnet-bearing areas appear as diffuse »clouds» outside of, but adjacent to the skarn areas. This relationship will be more closely touched upon during the discussion of the connection between the building of lime-silicates and the changes in the quartzites in the vicinity of the ore—lime-silicate areas.

From the facts mentioned above it is evident, that the formation of lime-silicates at the Adak Mine differs in certain respects from the kinds of lime-silicate formation generally met with in regionally metamorphosed areas or in ore deposits. The most common and widespread lime-silicate forming process is perhaps found in primarily heterogeneous calcareous rocks (sediments with lime-rich intercalations) in which, under conditions of increased temperature and pressure, a reaction between silica, iron, magnesia, and alumina on one hand and lime on the other has been brought about.

Lime-silicate masses formed in such a manner were named »reaction skarn» by Magnusson (21). Another kind of skarn formation, which is often connected with the formation of ore bodies and which is mentioned from different parts of the world, is thought to be caused by pneumatolytic or hydrothermal agencies acting on, and replacing limestones with the addition of silica, iron, magnesia etc. Similar conditions may be realized when intrusive masses invade limestones (8, 9). The formation of lime-silicates through addition of lime from lime-bearing solutions to lime-free rocks is only occasionally recorded in the geological literature (one example is the formation of hornblende in acid rocks at Gellivare, mentioned by Geijer (19, Fig. 24)). The skarn mineralization at the Adak Mine, however, is in a certain respect particular, as it affects rocks which are characterized by a former extraction of alkalis and lime. Silica, aluminium, iron and magnesium are chief constituents and the reactions at the mineralization are more simple to survey than in cases when additional constituents are present.

Concerning the source of the lime participant during the skarn formation at the Adak mine, it is at present impossible to give any definite utterance. It has been shown that the process is intimately connected with the invasion of the sulphides. It may furthermore be mentioned that the sulphide ores very often contain calcite, either comparatively evenly distributed among the sulphides or as irregular lumps or lenses, which may attain 1 m in width. Veins of pure calcite with reaction rims of lime-silicates have also been observed. Proceeding from these observations, it would seem probable that the added lime comes from the same source as do the sulphides. On the other hand, the possibility can not be dismissed, that lime in the sulphide-bearing solutions may emanate from the surrounding rocks. The alteration of acid or intermediate volcanites to cordierite- or andalusite-quartzites must have brought consider-

able quantities of lime and alkalis into solution. Possibly, this lime may, in a later stage of the evolution, react with the formation of lime-silicates or crystallize as carbonates together with the sulphides.

Description of the secondary quartzites.

Minerals.

As essential constituents in the quartziferous altered rocks the following minerals may be found: Quartz, chlorite, muscovite or sericite, biotite, cummingtonite or anthophyllite (gedrite), cordierite, andalusite, garnet (almandite) and magnetite. Ilmenite is generally present in addition to magnetite but is always quantitatively subordinate to this latter mineral. An-rich plagioclase may appear in small amounts. Apatite, zircon, titanite, rutil and tourmaline have been observed as accessory minerals.

Quartz, as a general rule, appears as rounded crystals of rather strongly variable dimensions (0.01—1 mm indicates the range of variation; 0.05—0.4, the most common dimensions.) The distribution of quartz is, in most cases, rather irregular in detail, with quartz-rich and quartz-poor flecks alternating, as seen in the thin sections.

Chlorite generally appears as fibrous aggregates in more coarse-grained quartzites, although it may sometimes form larger, separate flakes. The colour is in a normal thin section, light green with a pleochroism of yellow-white to yellow-green. The following optical constants may serve to characterize the mineral:

	α_1	γ_1	$\gamma-a$	
No. 1	1.621	1.623	0.002	+
No. 10	1.622	1.625	0.003	+

According to Winchell (34, Fig. 1), these optical properties answer to ripidolite with the approximate quotients:

	FeO : MgO	(Fe,Mg)O : Al ₂ O ₃
No. 1	45 : 55	76 : 24
» 10	47 : 53	78 : 22

Sericite and muscovite are characteristic constituents in certain quartzites in the innermost part of the Adak cupola, but sericite is also formed at a secondary and low-grade alteration of plagioclase or cordierite in the cordierite-bearing forms. In the coarser, mica-bearing quartzites, muscovite forms individualized flakes, up to 1 mm in length (most common dimensions 0.2—0.3 mm).

Biotite often occurs in the chlorite-bearing quartzites, there building irregularly-shaped flakes which are, as a rule, somewhat larger than the chlorite in the fibrous masses. In some types, however, biotite replaces chlorite entirely. The colour is, in normal thin section, light brown in the darkest position.



Fig. 2. Cordierite-cummingtonite-quartzite. Adak Mine. Nic. +. $\times 85$.

The lime-free *amphibole* in the quartzites is, in most of the thin sections investigated, seen to be a cummingtonite. Only in one case has anthophyllite been identified. The following optical constants give an idea of the composition of the Fe-Mg-amphiboles:

Sample No.		α	γ	$c : \gamma$	$2 V\gamma$	Fe : Mg
3	Anthophyllite (gedrite)	1.657	1.675		ab. 90°	52 : 48
9	Cummingtonite	1.652	1.681	19°	77°	56 : 44
11	»	1.651	1.680	19°	78°	55 : 45
14	»	1.649	1.678	20°	$77^\circ-79^\circ$	52 : 48
15	»	1.644	1.670	20°	$76^\circ-80^\circ$	44 : 56

The ratio Fe : Mg has been calculated with the aid of the diagram of Sundius expressing the relation between the refraction and the Fe-Mg-ratio, (29, Fig. 1; 30, Fig. 1). From the analysis No. VI of a rock consisting of cummingtonite, An-rich plagioclase, quartz and sporadic magnetite, the proportions Fe : Mg are found to be 49 : 51. As sample No. 9 represents the analysed rock, we find that the iron percentage is somewhat higher than is to be expected from the optical constants. Possibly an Al-content in the cummingtonite may influence the optical properties — if all CaO and Na₂O in the analysis were bound up in anorthite and albite there would be a remainder of Al₂O₃ which must enter cummingtonite. However, the percentage of Al₂O₃ is only 3 mol.-%. According to the results of Sundius (31) the anthophyllite should also be expected to contain a certain amount of Al and should therefore properly be

characterized as a gedrite, which is very probable also from a paragenetic point of view.

Cordierite is a very common mineral in the ore-quartzites of the Adak cupola. Generally speaking, it forms poikiloblastic individuals which, under uniform optical orientation, may approach a diameter of 4–5 mm; besides these, however, there occur minor, homogeneous grains, these being fairly free from inclusions. In some cases, clear, homogeneous, round or oval cordierites have been megascopically observed.

In normal thin sections, a faint yellowish pleochroism is often visible, especially close to inclusions of zircon or iron-bearing minerals.

The following optical constants have been determined:

Sample No.	a	γ	$\gamma-a$	$2 Va$
6	1.543	1.554	0.011	85°
20	1.542	1.551	0.009	77–78°
25	1.543	1.553	0.010	79–80°

Sample No. 6 is from a normal cordierite-cummingtonite-quartzite, No. 20 from a type with abundant garnet and No. 25 from a type with a high content of magnetite. The table shows the optical properties of the cordierites to be approximately the same in the three cases. According to Folinsbee (14), the values indicate the quotient $Fe^{2+} : Mg^{2+}$ to be about 3 : 7.

Andalusite occurs in those muscovite-rich quartzites which appear in the centre of the Adak cupola, at Lappliden, and then it forms irregular porphyroblasts which are often, to a certain degree, replaced by sericite. The mineral has not been observed in the quartzites at the Adak Mine, but it has been recorded, as pink crystals, in sulphide-ore from the Lindsköld Mine.

Garnet occurring in the quartzites is chiefly of almandite type, which is evident from the size of the unit cube, determined by X-ray powder photographs: $a_0 = 11.53 \text{ \AA}$ (28).

A determination of the refractive index was performed by Prof. G. Pehrman from Åbo. The mean of two measurements give: $n = 1.82 \pm 0.003$. This value answers to a quotient $Fe^{2+} : Mg^{2+} =$ about 9 : 1 (according to Stockwell (28, Fig. 2)). Spec. gravity, determined by pycnometer, was found to be 3.93, which value (according to Stockwell (28, Fig. 3)) answers to $Fe^{2+} : Mg^{2+} = 6 : 4$. However, the garnets in question contain numerous inclusions of quartz which cannot be removed by the separation and the value of spec. gravity found, is therefore certainly too low. For that reason, the refractive index must be decidedly more suited for indicating the $Fe^{2+} : Mg^{2+}$ -ratio than the specific gravity.

The garnet forms irregular poikiloblasts with a particularly variable number of inclusions. Needles of cummingtonite of pre-garnet formation can, in some cases, be followed with their original orientation through the poikiloblasts (Figs. 3 and 4).

Magnetite is a common mineral in many ore-quartzites. Certain quartzites, adjacent to the ore bodies, have a very characteristic spotted appearance

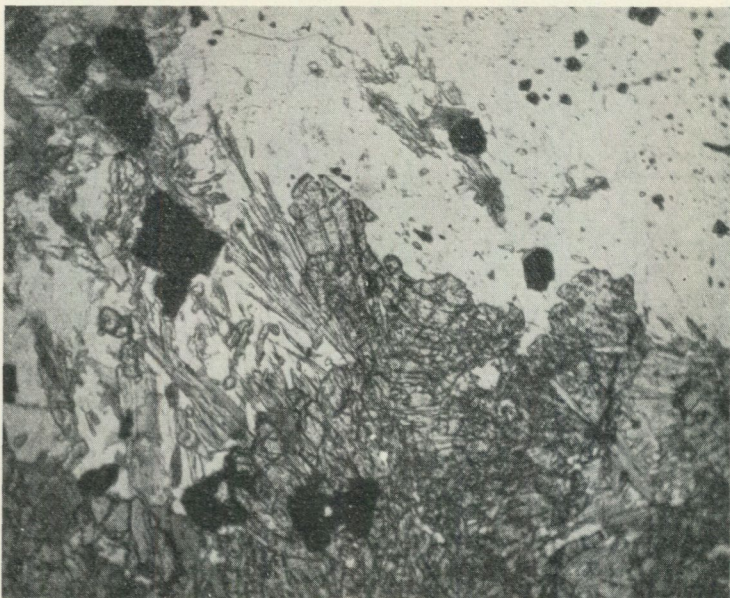


Fig. 3. Garnet-bearing cordierite-cummingtonite-quartzite. Adak Mine. Ord. light. $\times 25$.



Fig. 4. The same as fig. 3, Nic. +. The orientation of the cummingtonite needles is easily picked up in the garnet (black in the photograph).

with crystals (about 1 mm in diameter) of comparatively evenly distributed magnetite.

In analogy with magnetite, *ilmenite* is a frequent constituent in the quartzites, but it is always subordinate to magnetite. Generally, ilmenite appears as small separate grains, often with lath-shaped outlines in thin section (probably basal plates). Only in exceptional cases has ilmenite been found to occur as regular lamellae in magnetite.

Mineral associations of the ore quartzites.

The minerals of the ore quartzites occur in highly varying proportions. In some cases, chemically analogous quartzites have very different mineral composition — they represent then different mineral facies. In other cases divergencies in mineral composition reflect differences in chemical composition. In the last-mentioned event, various members may represent the same mineral facies. In table 6 p. 48—49, the analyses No. I and II represent those types of cordierite-quartzites which are the dominating rocks in the inner parts of the Adak cupola, No. 5 represents the muscovite-quartzites, occasionally andalusite-bearing, which sometimes take the place of the cordierite-quartzites. The most obvious chemical difference is the dissimilarity in the proportions between (Fe, Mg)O and Al_2O_3 , this being most clearly evinced by a comparison of the al- and fm-values for the three analyses. In Nos. I and II, the proportions al : fm are 22.5 : 70.5 and 28 : 68.5 respectively, in analysis No. V al : fm is 45.5 : 43. Thus the metasomatic alteration leading to a formation of ore-quartzites has brought about a metamorphic differentiation into, on one hand, rock-types rich in iron and magnesia and on the other, quartzites rich in alumina (see also the diagram, Fig. 17).

At the Adak Mine the Fe-Mg-rich quartzites only are present and we shall therefore consider these types only, in detail. In the quartzites at the Adak Mine the following mineral associations have been established (the minerals presented being the essential constituents):

1. Cordierite, cummingtonite, biotite
2. Cordierite, cummingtonite, almandite
3. Cordierite, cummingtonite, chlorite (sometimes almandite)
4. Cordierite, chlorite (sometimes biotite)
5. Cummingtonite, chlorite (sometimes biotite)
6. Cummingtonite, biotite
7. Chlorite, almandite (sometimes cummingtonite).

In addition, quartz is always present as an essential constituent in all these mineral assemblages. In most cases is further found more or less magnetite and An-rich plagioclase. However, the last-mentioned mineral may, at least in several cases, have been formed in connection with the origin of the lime-silicates and therefore the plagioclase will be considered in connection with the description of the lime-silicate rocks.

For an estimation of the kind and intensity of the metamorphic processes which are responsible for the formation of the »ore quartzites», the principles of mineral facies supply a valuable basis. According to our experience of different mineral facies, as it has been summarized by Eskola (6, Figs. 55 and 57), all minerals found in the quartzites, with exception of chlorite, can be formed under amphibolite facies conditions. Chlorite, on the other hand, is to be found in epidote-amphibolite facies or in green-schist facies. Microscopical investigations indicate with admirable clarity that, for the most part, chlorite was formed earlier than cordierite, cummingtonite, garnet and biotite. Consequently the mineralization must have developed under rising P-T-conditions. Even the microscopical survey gives the impression, that the different mineral assemblages alternate in such a manner as to hold the chemical composition of the quartzites constant within certain limits, that is, the parageneses mentioned represent, within certain limits, isochemical mineral associations. Fig. 5 shows the variations in mineral composition in a couple of ore-quartzites from the Adak Mine. The percentages of the various minerals are given in volume per cent and have been determined from thin sections. On account of the quartzites being rather heterogeneous in detail, isolated thin sections can not of course give precise information on the mineral proportions, so that the values in the figure must be considered to be comparatively approximate.

The samples Nos. 29 and 30 are from the drill hole sections which have rendered material for the analyses Nos. I and II. As can be seen from table 6, these two analyses are very much alike, the most striking difference being variations in the water content, and consequently the Niggli-values are specially well suited for illustrating the resemblance. Mineralogically the two rocks analysed are quite different, however (see Fig. 5). The samples taken for the volumetric determinations do not entirely correspond to those used for the chemical analyses, but nevertheless the figures in table 6 and Fig. 5 can be taken to show that chemically very similar rocks may appear in quite different mineralogical composition.

If we wish to obtain a measure of the grade of metamorphism which has been active in the formation of the ore-quartzites, two different factors, both of which can contribute to characterize this metamorphism, must be considered: 1. The differences in chemical composition between »ore-quartzite» and »primary rock» give a measure of the grade of »chemical metamorphism». 2. The mineralogical composition of the quartzites gives us an idea of the P-T-conditions prevailing at the metamorphism, and can further indicate to what extent chemical equilibrium was achieved in the various phases of the metamorphism. The agreement between the analyses of chlorite-rich (No. I) and cordierite-rich (No. II) quartzite discloses that the chemical alteration leading to the enrichment of iron and magnesia in the Adak cupola may, in the main, be already completed under the P-T-conditions characteristic of the chlorite formation.

In considering the P-T-conditions at the formation of ore-quartzites it is necessary to investigate to what extent the parageneses of the Adak Mine

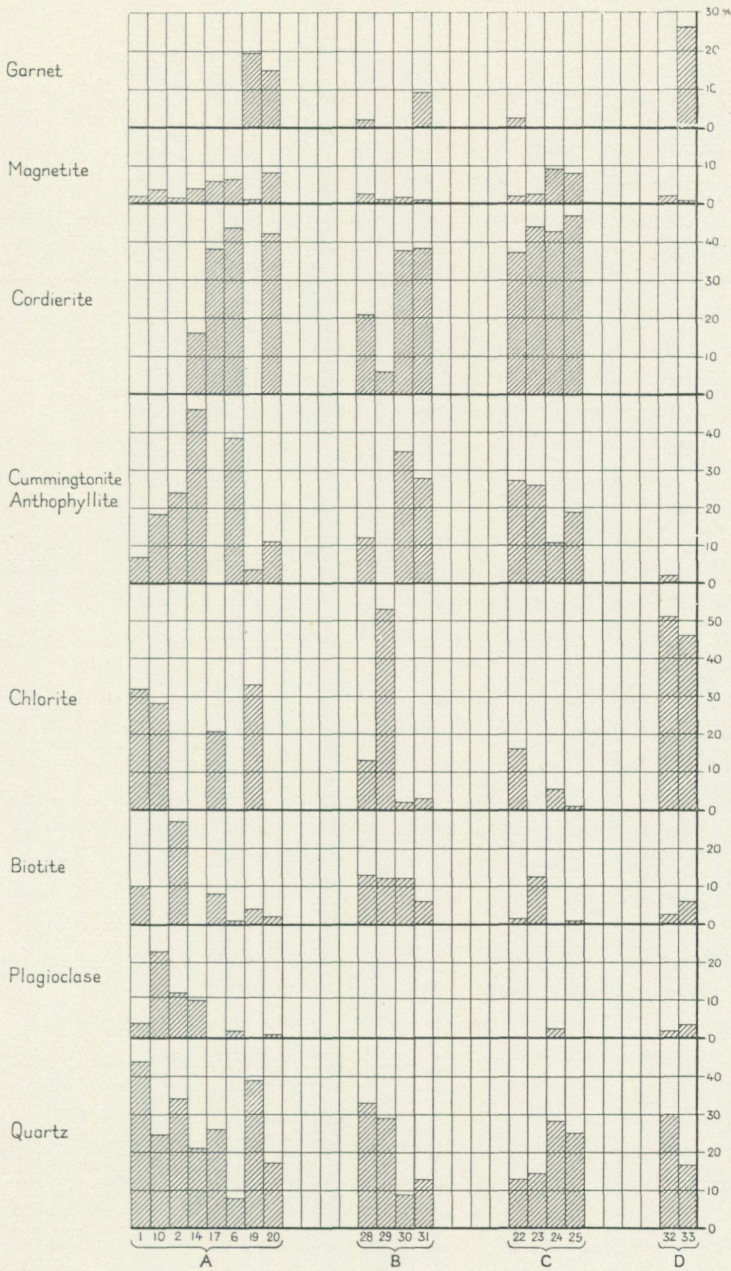


Fig. 5. Mineral compositions (expressed in vol. %) of some of the varieties of quartzite from the Adak Mine.

Group A — shows quartzites without consideration of the relative positions of the samples.
Group B — represents 4 samples from one and the same drill-hole within a section of 5 m.
Group C — the first 3 samples express the transition from normal cordierite-quartzite to a quartzite speckled with magnetite (in one drill-hole over a section of 6 m.).
Group D — shows the transition from garnet-free to garnet-rich quartzite around a fracture.

represent stable mineral associations. When applying the mineral facies principles the groups $(Al, Fe)_2O_3$ and $(Mg, Fe)O$ are generally regarded as two components. This is true only if Al^{3+} and Fe^{3+} on one side and Mg^{2+} and Fe^{2+} on the other are isomorphically exchangeable within limits of variation in the system considered. If water be present in sufficient amount for the formation of (OH)-bearing minerals, which is certainly the case in the present systems, water need not be considered as a special component. According to the phase rule then, in the presence of quartz, only two additional minerals can be expected, if true equilibrium existed during the mineralization. Biotite (or muscovite) can further be present since these minerals necessitate a third component, K_2O .

Considering firstly the garnet-free parageneses, it is evident that the association chlorite-cordierite-cummingtonite cannot represent an equilibrium. This mineral association represents instead, two mutually overlapping mineral facies and in the mutual proportions between minerals characteristic for higher temperatures and those characteristic for lower temperatures, one is able to obtain a certain measure of the thermal effect of the metamorphism.

A very common association is cordierite—chlorite. This association may intimate a certain degree of enrichment in Al in relation to the other quartzites when cordierite contains proportionally more Al_2O_3 as compared with $(Fe, Mg)O$ than chlorite. In conformity with this, the association chlorite—cummingtonite (or anthophyllite), which has also been found, to a certain degree represents an enrichment of $(Fe, Mg)O$. Hence an alteration between these two associations indicates a tendency towards the same metamorphic differentiation, which has previously been mentioned and which leads to a separation into, on one hand, muscovite- and andalusite-bearing quartzites and, on the other, cordierite-cummingtonite-chlorite-bearing quartzites. Eskola proposes anthophyllite and chlorite to be a stable association in epidote-amphibolite facies (6, Fig. 57), whereas cordierite and chlorite are regarded as an unstable association. The comparatively common occurrence of chlorite and cordierite in association indicates, however, a possibility of both cordierite—chlorite and cummingtonite—chlorite being stable in a certain (probably quite small) P-T-interval. If cummingtonite and cordierite were formed at the expense of chlorite, under increasing P-T-conditions and with constant chemical composition, it must be expected that both minerals resulted at the same time and in definite mutual proportions. The possibility of a »subfacies» with chlorite »separating» cummingtonite and cordierite has been denoted in the diagram, Fig. 17, by broken lines. Fig. 6 shows the proportions between chlorite, cordierite + garnet and cummingtonite in the samples where volumetric determinations were made. The projection points lying in the central parts of the triangle are remarkably few. The percentages of biotite in the quartzites is also represented in the diagram and from this it is evident that biotite may be a frequent constituent, both in chlorite-rich and in chlorite-poor quartzites. Microscopic investigation of powder of different quartzite types (those with megascopically observable cordierite porphyroblasts being especially considered) dis-

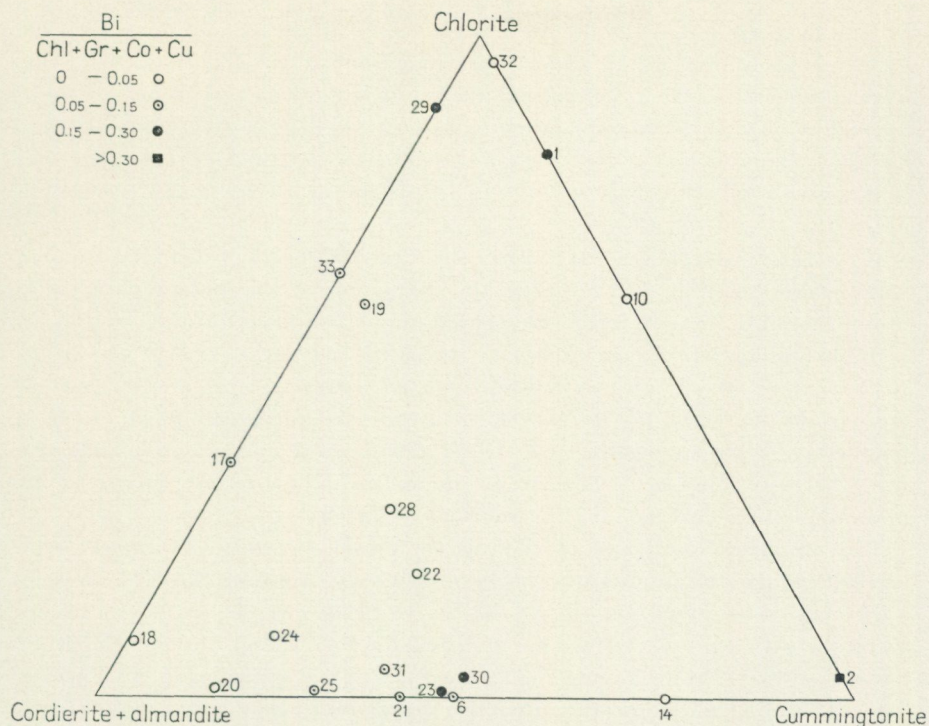


Fig. 6. The distribution of various Fe-Mg-containing silicates in the quartzites. The proportions indicated in vol.-%. Bi = biotite, Chl = chlorite, Gr = garnet, Co = cordierite, Cu = cummingtonite.

closed the following frequency of different associations (only essential minerals being considered):

Chlorite + cordierite	6	samples
Chlorite + cordierite + cummingtonite	3	»
Cordierite + cummingtonite	4	»
Cummingtonite	1	»
Chlorite	1	»

Whether or not cordierite and chlorite can occur in stable association can of course, not be definitely answered, even by means of this survey, but the possibility of a stable association cordierite—chlorite seems not improbable.

The postulation that only two stable Fe-Al-Mg-silicates can exist in an equilibrium is founded on the assumption that $(\text{Fe,Mg})\text{O}$ and $(\text{Al,Fe})_2\text{O}_3$ are regarded as the two components of the system. If, however, minerals occur in which Fe^{3+} and Al^{3+} or Mg^{2+} and Fe^{2+} are not exchangeable, each ion must be considered separately, whereupon additional minerals may occur as stable constituents. Now cordierite can contain iron within certain limits only (under the P-T-conditions in question) and consequently, we can expect some additional mineral, characterized by an enrichment of Fe^{2+} . As has

previously been stated the ore quartzites often contain magnetite as an essential constituent. As Mg^{2+} cannot enter magnetite it is evident that e. g. the association cordierite — cummingtonite — magnetite can represent an equilibrium. A certain symbatism between magnetite and cordierite is also noticeable in the volumetric analyses: samples, characterized by especially high percentages of cordierite (Nos. 17, 18, 10, 21), have also remarkable contents of magnetite.

In analogy with magnetite, almandite can also be regarded as a mineral which takes up iron. Even during the discussion of the mineral parageneses of the Orijärvi Area, Eskola emphasized that almandite must be considered a stable mineral when associated with cordierite and anthophyllite. The reason is that under the P-T-conditions in question, garnets rich in Mg^{2+} are not stable and therefore the garnets formed have a limited ability to take up magnesia as compared with iron. The appearance of magnetite or almandite may therefore represent a megascopically visible indication of a change in the iron:magnesium-quotients of the »normal» quartzites.

The analyses Nos. I and II in table 6 represent quartzites without garnet and with magnetite in insignificant quantities only. Analysis No. III represents a quartzite with abundant garnet (Nr. 31 in fig. 5), which occurs in close association with the quartzites characterized by Nos. I and II. No. III differs from Nos. I and II in having higher FeO-percentages and lower SiO_2 -percentages. In the Niggli-values the difference is apparent inasmuch as mg decreases from 0.42 and 0.44 in Nos. I and II respectively to 0.30 in No. III. Thus the analyses confirm the suspicion that the garnet-bearing type represents a quartzite enriched in iron as compared with the garnet-free quartzites. Since the garnet is obviously of later formation than cordierite and cummingtonite, it seems very probable that the formation of this mineral was brought about by an influx of iron at a later stage of the metasomatic processes. This aspect will be considered in detail in connection with a discussion of the processes which have given rise to the lime-silicates.

Analysis No. IV represents the previously mentioned quartzite, very readily characterised megascopically, due to the presence of magnetite spots. A comparison of this analysis with Nos. I and II demonstrates an enrichment in iron ($mg = 0.27$ in IV, 0.42 and 0.44 in I and II). No. IV differs from analysis No. III, inasmuch as the iron in IV is mainly present as Fe^{3+} . This is demonstrated by the Niggli-values where a higher o-value for No. IV than for Nos. I, II and III is seen.

Mutual relations of the different quartzites.

The occurrence of a great number of vertical drillholes makes it possible to effectively survey the distribution of the different quartzite types in the ore-bearing area of the Adak Mine. It would then be close at hand to suppose that there should be some kind of zonal arrangement of the different types around the ore bodies. In Fig. 1 was demonstrated, how the garnet-bearing

rocks often are to be found in the immediate vicinity of the ore bodies or sulphide-bearing areas, although the connection is not so regular that garnet is always present in quartzites along the limits of the ore-bodies (which can even be seen in Fig. 1) and neither are garnet-bearing quartzites *always* bound to sulphidized zones. It must, however, be remembered that sulphides are not always deposited in the fractures which have served as channel-ways for the supply of the mineralizing solutions. At least in some cases, when garnets were found without any direct connection with sulphides, the formation of the garnets is likely to have been caused by the sulphide-bearing solutions. It has been found, for example, that garnets have developed along fractures which most probably have been used by ore-bearing fluids and which may grade into sulphide-bearing fissures. The samples Nos. 32 and 33 in Fig. 5 show the transition from garnet-free to garnet-bearing quartzite, skirting a fracture of this kind. The figures disclose the garnets to be formed mainly at the expense of chlorite, some sericite and quartz.

The magnetite-rich quartzites are also varieties which occur close to the sulphide bodies. This type of quartzite has been observed on several occasions in drill-holes, forming completely sulphide-free portions between ore-sections, and as fragments of ore-free quartzite enclosed in high-grade ore. Thus the magnetite-rich quartzites occur in the same general manner as the garnet-bearing quartzites. In the drill-holes are found gradual transitions from normal, more or less chloritic, quartzites over spotted types with abundant cordierite, to massive, magnetite-rich varieties. The samples Nos. 22, 23 and 24 in Fig. 5 illustrate such a kind of transition from a section extending 6 m in a drill-hole. No. 25 is from another drill-hole and represents a pronounced magnetite-spotted quartzite, occurring between two ore sections.

The distribution of the chlorite-rich and the chlorite-free quartzites is mostly quite irregular. If the quartzites of the Adak cupola are considered as a whole, a certain development of cummingtonite-bearing types is often observed adjacent to the sulphidized areas; but on the other hand, a survey of the results from drill-holes of the Adak Mine discloses that no regular and characteristic arrangement of the different ore-quartzites, mutually or relative to the ore bodies, exists. Sulphide mineralization is often found in quartzites very rich in chlorite and sulphide ore bodies sometimes traverse boundaries between different types of quartzite. In some drill-holes, quartzites with chlorite predominant and others with cordierite and cummingtonite predominant alternate, but by combining the results from adjacent drill-holes very irregular boundaries between the different quartzite-types generally result. In most cases, no agreement with the primary layered structure of the cupola can be discerned. The samples Nos. 28, 29, 30 and 31 in Fig. 5 show, in a mineralogical respect, how different quartzites can succeed each other within a fairly limited vertical section. The chemical analyses Nos. I, II and III answer approximately to the samples Nos. 28, 30 and 31 respectively, showing the chemical variations in the same section. The agreement between analyses I and II and the general mutual distribution of the chloritic and the chlorite-free quartzites, indicate

that the mineralization has taken place under P-T-conditions very close to the transition point of chlorite into biotite and therefore small variations in temperature and pressure may cause considerable variations in the mineralogical composition of the altered rocks.

Lime-silicate (skarn) rocks.

Survey of the lime-silicate rocks, their mineralogy and mutual relationship.

The following minerals may appear as essential constituents in the lime-silicate or skarn rocks: Epidote or zoizite, pyroxene, hornblende, andradite and An-rich plagioclase. In a certain respect cummingtonite should also be considered in this connection, since an intensified cummingtonitization often has accompanied the formation of the skarn masses proper. In addition, the skarn parageneses are more or less calcite-bearing. Small amounts of quartz are sometimes present, especially in associations carrying epidote. Titanite is a rather common mineral, but it occurs in very variable proportions. Finally apatite has been observed in a few cases.

The large compact masses of skarn rocks have in part a composite mineralogical composition, but again, may be almost monomineralic. Pure epidote, pyroxene and hornblende masses can be discerned; even megascopically the boundaries between the various forms are, however, then diffuse. A certain succession between the various types of skarn rocks is also discernible: Pyroxene rocks are distinctly younger than the hornblende rocks and sometimes well-defined fragments of hornblende-skarn are observable in the pyroxene rocks (see Fig. 9). The epidote rocks are younger than the pyroxene skarn, which is often penetrated by epidote veins. When the skarn rocks border on the quartzites, a very regular zonal arrangement of the skarn minerals is often visible, the individual zones however, attaining a width of only one or two centimeters. In spite of these insignificant dimensions this zonal arrangement is very interesting and renders valuable information as to the development of the skarn-forming processes.

The most distinctive zonal arrangement is to be observed along narrow veins of skarn (with or without sulphides) which penetrate the quartzites. It is evident, from what has been mentioned previously in this paper, that a zonal arrangement on a larger scale can not be expected, since the large, compact skarn masses were found to have originated by a coalescence of small skarn veins. In thick veins or in accumulated masses, we must assume the different skarn zones to superimpose each other, and consequently the regular zonal arrangement along the narrow veins has been obliterated.

In the veins or veinlets of skarn minerals, epidote often constitutes the central section. When sulphides are present, epidote shows a pronounced tendency to form accumulations with these. The epidote zone, as this central portion of a skarn vein can be designated, may sometimes be almost mono-



Fig. 7. Pyroxene-epidote skarn veins (appear lighter than the surroundings) brecciating cordierite-quartzite. Dark, hornblende-rich reaction zone with the quartzite. In the centre, a small inclusion of quartzite with a reaction zone. Roof of a tunnel, 165 m.-level, Adak Mine; 1 : 10.

mineralic, sometimes, however, there is a mixture of epidote and pyroxene, with the former mineral dominating. Finally the epidote zone may be composed of coarse epidote crystals along the walls of the fractures which served as channel-ways for the mineralizing solutions.

Outside the epidote zone there is a zone characterized by pyroxene, where however, epidote, hornblende and anorthite may appear as subordinate constituents. Garnet may be present in comparatively large amounts together with pyroxene in sulphide-carrying skarn veins, the garnets then generally being concentrated in the central parts of the veins. In such cases epidote is lacking.

Outside the pyroxene zone there is always a dark border, generally ca. 1 cm wide, containing abundant hornblende. On several occasions a light zone, also about 1 cm wide, is visible in the quartzite at the contact with the hornblende skarn. The appearance of the different skarn zones is illustrated in figs. 7—9 (the light zone between hornblende and normal quartzite is particularly obvious in fig. 8). Figs. 7 and 8 both demonstrate pieces of quartzite, (surrounded by reaction zones) to be entirely included in the skarn masses. From the figures, it can be seen that the boundaries between the outer reaction zones are comparatively distinct, whereas the boundaries between the epidote zone, the pyroxene zone and pure hornblende skarn are more irregular and diffuse.

Microscopic examination shows the light border between quartzite and

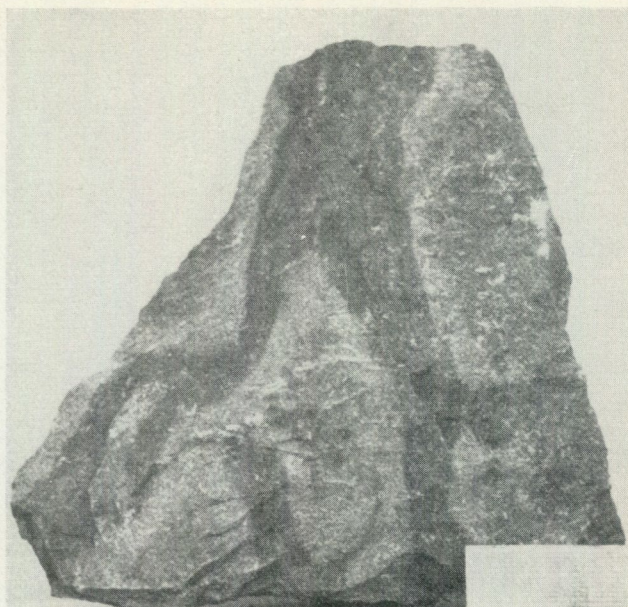


Fig. 8. Skarn-schlieren in chlorite-rich quartzite. Markedly light reaction-zone in the quartzite. Adak Mine, 165 m.-level.

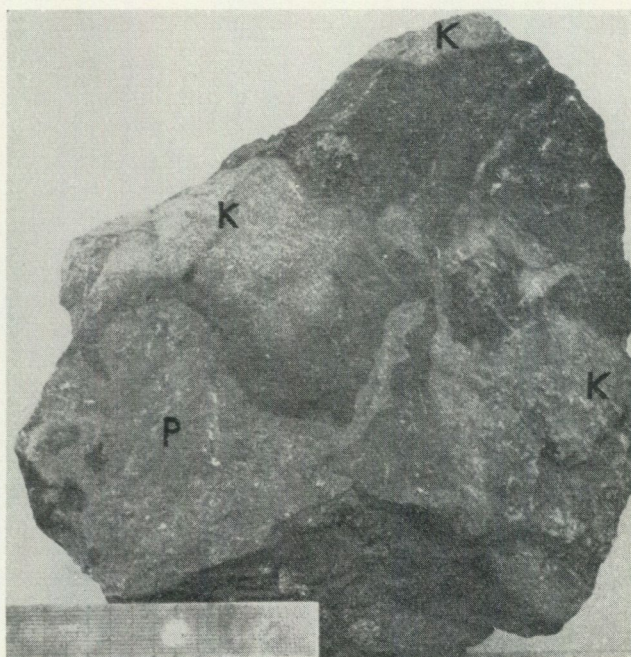


Fig. 9. Skarn veins in quartzite. The hornblende-rich skarn is dark. Quartzite = K, pyroxene skarn = P (contains fragments of hornblende-skarn to the left of the photograph).

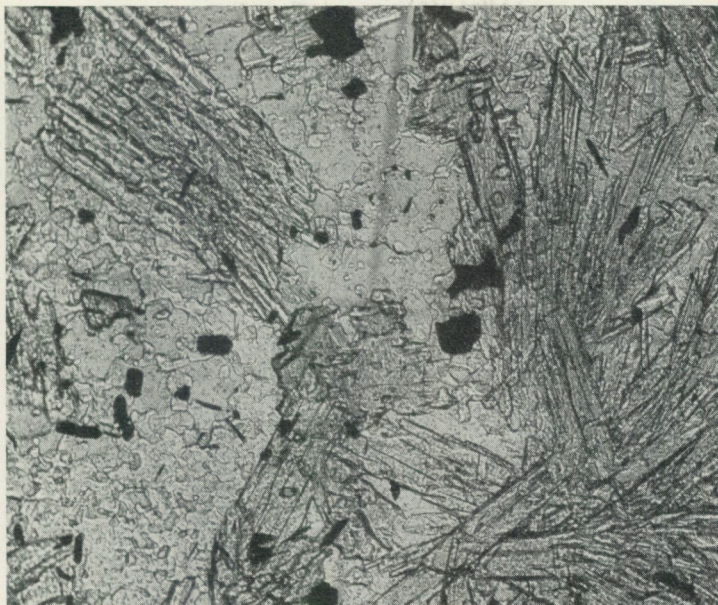


Fig. 10. Cummingtonite-anorthite-quartzite. Ord. light. $\times 85$.

hornblende to consist of cummingtonite, quartz and plagioclase rich in anorthite in varying proportions (see fig. 10). In addition, a certain amount of magnetite is present in most cases.

The *plagioclase* often appears in a poikilitic variety and has as such, a very irregular extinction which makes determination of the composition according to common methods very difficult. Determination of refractive index gave the following values:

Samples No.	a_1	γ_1	% An.
3 (see fig. 15)	1.658	1.579	84—86 %
15 "	1.568	1.578	84—85 %

The optical properties of cummingtonite have already been given under the description of the minerals characteristic of the ore-quartzites.

The «hornblende-zone» is, by microscopic examination, found to consist almost exclusively of hornblende and plagioclase. In one of the samples investigated sericite, obviously an alteration product of plagioclase, was found to be abundant. Quartz is generally absent and has only been observed in any considerable quantity in one of the samples examined. Magnetite is present in several samples, as well as small amounts of titanite and calcite. Fig. 11 shows this type of skarn rock in a very characteristic development.

The composition of the plagioclase has been estimated from the refractive index:

Fig. 11. Hornblende-anorthite-skarn. Ord. light. $\times 50$.

Sample No.	α_1	γ_1	% An
5 (see fig. 15)	1.574	1.586	96 %
8 »	1.574	1.586	96 %
12 »	1.573	1.585	94—95 %
13 »	1.576	1.588	100 %
16 »	1.574	1.585	95 %

Hornblende, when appearing together with plagioclase as regular reaction zones with the quartzites, shows mainly the same variations as hornblende from larger compact masses or that occurring as inclusions in pyroxene- or epidote-skarn. In most cases they can be characterized as common green hornblendes, although, inhomogeneous hornblende with practically colourless centres have also been observed. Furthermore, one and the same thin section may exhibit both darker and lighter hornblende in different parts of the slide. The colour-variations are not so great, on the other hand, as to indicate any noteworthy variations in the Fe-Mg-ratio. Hornblende with the highest colour shows the following pleochroism: γ light blue-green; β bright grass-green; α yellow white. In some cases, a deeper bluish-green hornblende has developed close to sulphide grains. The same kind of hornblende has also been observed in the cummingtonite-plagioclase zone, the cummingtonites then being transformed to blue-green hornblende adjacent to sulphide grains. However, the formation of such blue-green hornblende is quite insignificant, as compared with the formation of the skarn minerals in general and is always bound to contacts with sulphides. It can therefore be regarded as a last phase of the skarn formation — a phase characterized by the crystallization of the sul-

phides. Since the sulphidization in part can be said to »cut» the zonal arrangement of the skarn minerals this last formation of hornblende is not directly connected with the main skarn forming phase.

The variations in the optical properties of the hornblendes illustrate to a certain degree the divergencies in their composition:

Sample No.	a_1	γ_1	$c : \gamma$	$2V_a$
13 (see Fig. 15)	1.628	ab. 1.655		ab. 82°
12 »	1.637	1.662	15°	75—76°
16 »	1.641	1.666	16°	75°
13 »	1.645	ab. 1.668		75°
8 »	1.647	1.671	14—15°	71—73°
Hornblende skarn	1.647	1.671	15°	72—74°

The constants from No. 13 refer to a very heterogeneous hornblende with a practically colourless kernel (the uppermost values) and a bright-green border (the fourth value from the top). On account of the two types being intimately intergrown, it was very difficult to make exact determinations. The most frequently occurring hornblendes are represented by No. 12 and downwards, in the table. The values have been arranged according to rising refractive index, $2V_a$ then showing a tendency to decrease, which is in harmony with our knowledge of the variations connected with increasing $Fe^{2+} : Mg^{2+}$ -ratio. As will be shown later on, a substitution of Si^{4+} through Al^{3+} also influences the refractivity. In spite of the numerous investigations concerned with the relationship between optical properties and chemical composition which have been published of late, it is still a precarious matter to treat the mutual proportions of the various components within the hornblende group, relying merely on optical data. Analysis No. VIII represents a practically pure hornblende skarn (the optical constants are given in No. 12). Besides the hornblende, sulphides and some quartz occur. If iron for formation of pyrrhotite and chalcopyrite be subtracted from the analysis, the following molecular proportions are obtained.

SiO ₂	8 801	K ₂ O	19	
Al ₂ O ₃	478	H ₂ O	1 343	
TiO ₂	45	0.5 F	268	theoretical
Fe ₂ O ₃	229			values
FeO	1 440	SiO ₂	49.2	48.0
MnO	38	2 Al ₂ O ₃	5.4	5.4
MgO	2 401	TiO ₂ + 2 Fe ₂ O ₃ + FeO + MnO + MgO.	24.6	27.8
CaO	1 794	CaO + 2 Na ₂ O + 2 K ₂ O	11.5	12.5
Na ₂ O	108	H ₂ O, F	9.3	6.3

In the group, $CaO + 2Na_2O + 2K_2O$ (= 11.5 %) the alkalis constitute 1.4 %. Assuming a substitution of Ca^{2+} by $(Na,K)^{1+}$ to be compensated by an equivalent substitution of Mg^{2+} by Al^{3+} , a surplus of Al^{3+} (corresponding to 4 % Al_2O_3) is obtained which must be distributed over other positions in the hornblende structure. According to the general hornblende formula, this quantity of Al^{3+} should to the same degree substitute Si^{4+} and Mg^{2+} .

If we calculate the molecular proportions of a hornblende with such a substitution, the values as given in the extreme right column are obtained. As will be seen, the values as found by the analysis for SiO_2 and $(\text{H}_2\text{O},\text{F})$ are higher than, and those for $(\text{Fe},\text{Mg})\text{O}$ and CaO are lower than, the theoretical values. The surplus of SiO_2 may very probably be caused by a slight admixture of quartz, which could not be removed at the separation. Besides this, the comparatively high hydroxyl content complicates the question in the present case and makes it difficult to analyse the substitution in detail.

The proportion iron : magnesium, is a very important factor in the discussions on the evolution of the skarn-forming process. From the analyses,

the quotient
$$\frac{\text{MgO}}{2\text{Fe}_2\text{O}_3 + (\text{Mg},\text{Fe},\text{Mn})\text{O}} = 0.555$$
 can be calculated. The analysis

No. VIII makes it possible to calculate the same quotient for another hornblende, represented by No. 8 in the table. (Analyses No. VII refers to a hornblende-plagioclase rock, but on account of all iron and magnesium being bound up in hornblende, the quotient can be calculated from the molecular proportions of the analysis.) The quotient in question is found to be 0.540, which is very near the same value as was found in analysis No. VIII. Assuming similar substitutions in the two hornblendes, this degree of correspondence in the Mg : Fe-ratio is in poor agreement with the difference in the refractive indices this being 0.009—0.010. From diagrams showing relationships between the optical properties and composition of normal hornblendes, published by Foslie (15, Fig. 1) and Sundius (32, Fig. 8) a difference of the Mg : Fe-quotient amounting to at least 0.1 is to be expected in hornblendes with high Al-contents and in hornblendes with less Al the difference would be still greater. If, however, we try to calculate an approximate composition of the hornblende from the analysed rock No. VII, we find that in this case Al^{3+} must replace Si^{4+} to a greater extent than was the case in the hornblende represented by analysis No. VIII. The proportions between Al^{3+} (in four-coordination) and Si^{4+} can be written, in the former case as 0.7 : 7.3 (possibly still higher Al^{3+} content) and the second case as 0.3 : 7.7. These differences contribute to explain the differences in refraction (see the diagrams cited above). The variations of refraction of the hornblendes, as given in the table, thus reflect not only variations of the Mg : Fe-quotients, but also variations in the substitution of Si^{4+} by Al^{3+} . Disregarding the colourless hornblende in the table (Nr. 13 at the top) Mg : Fe-quotients most probably display comparatively small variations. This is also indicated by the small variations in the optical angle.

Pyroxene appears in complex skarn rocks, associated with hornblende, epidote and anorthite or with garnet as well as in monomineralic masses. The pure pyroxene skarn rocks form bright-green, dense masses, which by microscopical examination are found to be built up of small, equi-dimensional rounded pyroxene grains (see Fig. 12 upper part). Small individuals of hornblende, forming strongly corroded relics, have been observed even in the purest pyroxene masses. In the complex skarn rocks, the pyroxene is often developed as larger crystals. Fig. 13, left part, shows coarse pyroxene-skarn

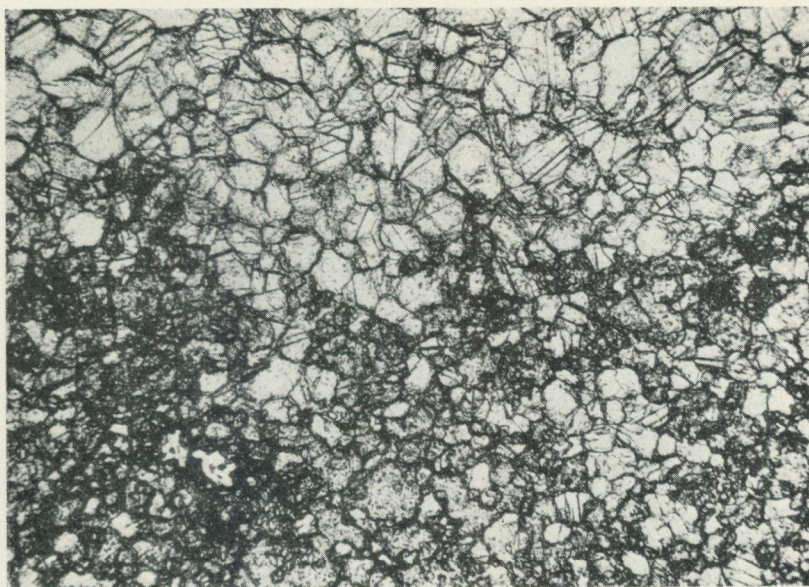


Fig. 12. Pyroxene-garnet-skarn (garnet mainly in the lower portion of the photograph). Ord. light. $\times 50$.

with irregular remnants of green hornblende. In normal thin sections the pyroxene displays a faint greenish colour and shows a weak pleochroism (colourless to faint greenish). The optical properties have been found to vary but slightly, as is shown by the following values.

Sample No.	a	γ	$c : \gamma$	$2 V\gamma$
7 (see Fig. 15) from the zone outside	1.689	1.714	$41^{\circ}-42^{\circ}$	56°
13 and 14 in Fig. 15	1.687	1.712	41°	55°
Pyroxene skarn with remainders of hornblende..	1.696	1.722	45°	56°

According to Winchell (33, Fig. 145) these properties correspond to a pyroxene mainly of diopside-hedenbergite type but with an admixture of 12–18 % clinoenstatite and with approximately diopside equal to, or somewhat more than of hedenbergite. From analysis No. IX of pyroxene skarn the following molecular proportions are obtained:

		Mol.-%		Mol.-%	
SiO ₂	8 565	50.5	MgO	2 098	12.4
Al ₂ O ₃	297	1.7	CaO	4 041	23.8
TiO ₂	18	0.1	K ₂ O	12	0.1
Fe ₂ O ₃	161	1.0	Na ₂ O	42	0.2
FeO	1 235	7.3	H ₂ O	272	1.6
MnO	37	0.2	F	195	1.1

As can be seen, these values do not indicate any »intermixture» of clinoenstatite. On the other hand, the proportions Fe : Mg agree fairly well with

the results obtained from Winchell's diagram. In this analysis the remarkably high contents of H₂O and F make it very difficult to obtain an idea of the substitutions in detail. The high SiO₂-content may, to a certain degree, be due to a slight intermixture of quartz.

Garnet is a rather common constituent in some pyroxene skarn rocks, the mineral then appearing as irregular, fine-grained aggregates (as Fig. 12, lower part). In compact sulphide masses beautifully idiomorphic garnets with reflecting faces have sometimes been found. These garnets may attain 3 cm in diameter. Finally, garnets have been observed as idiomorphic crystals in calcite.

Determinations of the dimensions of the unit cell discloses the garnets in the skarn rock and in the sulphide masses to be of andradite type. Determinations of spec. gravity and refraction give an idea of the proportion between andradite and grossularite, and analysis No. X shows the composition of a garnet in compact sulphide ore.

	Spec. gr.	n	a ₀
Garnet from garnet-pyroxene skarn...	3.760 ± 0.005		11.95
Garnet from copper ore (Analysis No. X)	3.770 ± 0.005	1.85 ± 0.005	11.96

Analysis No. X: Andradite from high-grade copper ore. Adak Mine.

Analyst: A. Bygdén, Geol. Survey of Sweden.

		mol. prop.
SiO ₂	35.70	599.4
TiO ₂	0.20	3.1
Al ₂ O ₃	5.42	53.2
Fe ₂ O ₃	22.99	144.0
FeO (Approx.)	2.16	30.1
MnO	0.29	0.41
MgO	0.19	0.47
CaO	32.19	574.0
BaO	—	—
H ₂ O ⁺¹⁰⁵	0.40	
H ₂ O ⁻¹⁰⁵	0.09	
CuO	0.30	
S	0.35	
	100.28	
Subtracted O for S	0.18	
	100.10 %	

If an amount of FeO, sufficient for the binding of S in chalcopyrite and pyrrhotite be subtracted, and the remaining oxides be combined to form the components andradite, grossularite, pyrope and almandite (+ spessartite), the constitution of the garnet may be expressed in the following figures: 72.6 % andradite, 23.4 % grossularite, 0.06 % pyrope, 2.4 % almandite (+ spessartite). These figures agree very well with those which can be calculated from spec. gr., refraction and cell dimensions by using the diagrams of Stock-



Fig. 13. Complex skarn. Pyroxene with hornblende relics to the right, anorthite in the middle, epidote and sulphides to the left in the photograph. Ord. light. $\times 25$.

well (28, Fig. 2 and 3). As the physical properties coincide very closely, in the two garnets examined, their chemical composition is also most probably very similar.

Epidote and zoisite appear very often together with sulphides and at least in many cases epidote or zoisite seem to develop from pyroxene, hornblende or anorthite at the crystallization stage of the sulphides. Fig. 13 (right part) shows zoisite, epidote and sulphides replacing skarn masses with abundant anorthite. As has been mentioned previously however, epidote also forms compact masses. A microscopical examination discloses the epidote in such cases also to contain relics of hornblende (see Fig. 14) or pyroxene. In epidote of this kind, the following refractive indices were determined: $\alpha = 1.732$, $\gamma = 1.766$. From the diagram of Winchell (33, Fig. 237) these values are found to indicate a quotient $\text{Fe}^{3+} : \text{Al}^{3+}$ of approximately 1 : 3. In its purest conditions epidote appears as more or less well-developed, short prisms, very often associated with calcite. Hornblende may also occur in calcite fissures, intersecting the complex skarn masses. In normal thin sections, epidote generally has a faint pleochroism, ranging from yellow-green to colourless.

In several cases, *sericite* has been found as a decomposition product of the An-rich plagioclase. Sometimes the alteration leads to true pseudomorphs of sericite after plagioclase, but more commonly, the sericite appears as scattered flakes in the plagioclase. Even in cases where sericite forms but a very small part of the plagioclase-sericite mass, a faint red colour can be megascopically discerned. This type of alteration of anorthite-rich plagioclase, known as

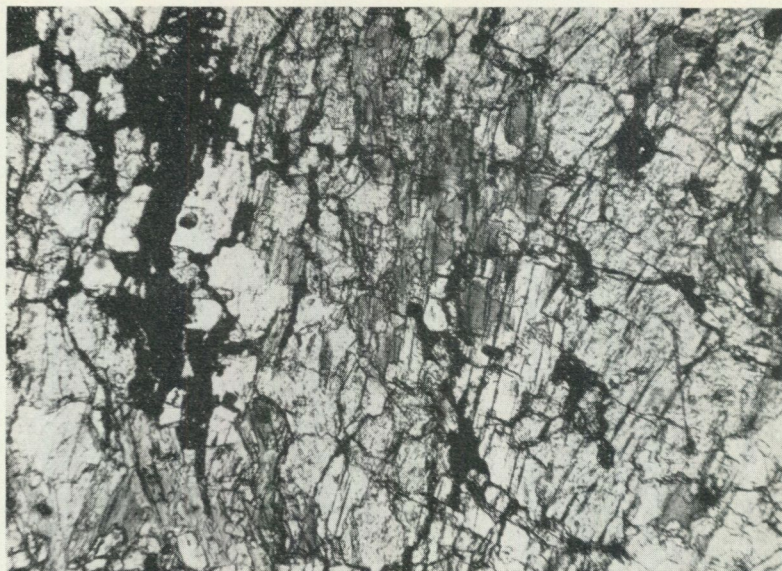


Fig. 14. Epidote-skarn with relics of green hornblende (light grey). Black = sulphides. Ord. light. $\times 50$.

amphodelitization, has been formerly described by the present author from several ore deposits in the Skellefte District, the Adak ores then being included (17).

Titanite is a common mineral in the skarn parageneses, the sizes of the individual crystals as well as the total amounts of the mineral, however, showing considerable variations from one case to another. In skarn rocks with abundant epidote or in complex skarn masses titanite needles 2—5 mm in length have been observed. In general, the individual needles do not exceed 1 mm and transitions to types where titanite appears only as granular aggregates are often found. In the larger individual crystals, idiomorphic crystal shape is often observed.

Magnetite and *ilmenite* are also present in the skarn rocks. In the compact skarn masses, magnetite is generally very subordinate. On the other hand, veins up to 1 cm wide have been met with in dense pyroxene-skarn. Ilmenite as minor rounded grains is more common and often occurs evenly distributed. In some cases, the amounts of ilmenite seem to increase from the quartzites towards the skarn rocks.

Survey of the mineralogical and chemical changes during the skarn formation.

The mineralogical composition of the different skarn zones and the mutual relations between the various zones give us an idea of the course of the mineralization. Fig. 15 is a survey of volumetrical analyses from 6 series of thin

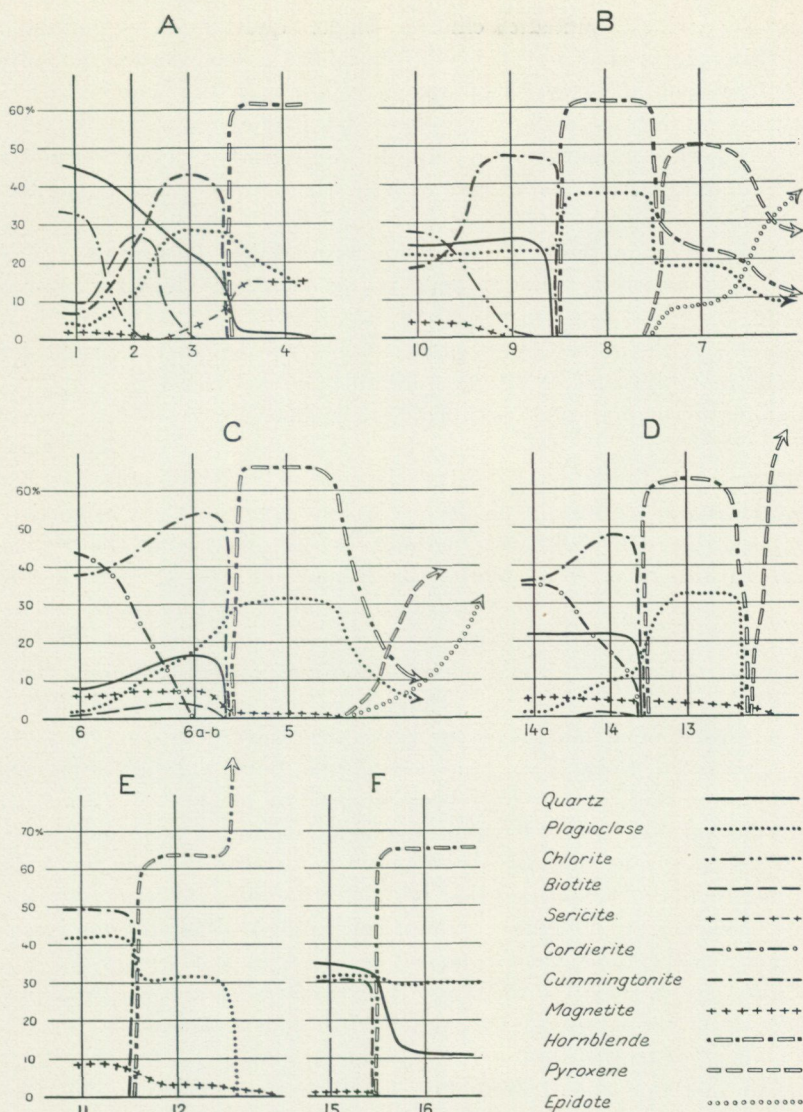


Fig. 15. Volumetric analyses of 6 series of thin-sections (A—F), illustrating the mineralogical changes from quartzite (to the left in every series) to skarn. The vertical lines indicate the analyzed section; the tendency of change when further on in the skarn-veins is indicated (by the arrows on the respective curves).

sections, each series showing the mineralogical changes from quartzite to skarn rock. The samples have been chosen to exemplify different types of contact relations. Megascopically, the following zones could be discerned:

A. Chlorite-rich quartzite—»light quartzite» (cummingtonite-anorthite-quartz zone, 1 cm)—hornblende-rich skarn (hornblende-anorthite zone, 0.5—1 cm)—ore zone with skarn-minerals (2—5 cm).

- B. Quartzite with abundant chlorite—»light quartzite» (cummingtonite-anorthite-quartz zone, 1—1.5 cm)—hornblende-rich skarn (hornblende-anorthite zone, 1—1.5 cm)—pyroxene skarn with amphotelite—ore zone with skarn minerals (epidote, pyroxene, hornblende, anorthite, 5—10 cm).
- C. Grey cordierite-cummingtonite-quartzite—hornblende-rich zone (hornblende-anorthite-zone, 2 cm)—ore zone with skarn minerals (epidote, pyroxene, 3—6 cm).
- D. Grey cordierite-quartzite—cummingtonite-quartzite—hornblende-rich zone (hornblende-anorthite zone, 1 cm)—pyroxene skarn (1.5—2 cm)—coarse calcite.
- E. Quartzite with abundant cummingtonite—hornblende-rich zone (hornblende anorthite zone, 1—2 cm)—hornblende skarn.
- F. Cummingtonite-quartzite—hornblende-rich zone.

In the series A, the first step of the skarn formation (represented by No. 2) is indicated by an increase of plagioclase as compared with the original rock. Contemporaneously-formed cummingtonite is also increasing, biotite is an essential constituent whereas chlorite has disappeared. No. 3, representing the plagioclase-cummingtonite zone proper, discloses all biotite and chlorite to be replaced by cummingtonite and anorthite, and quartz to have decreased. In the next zone, No. 4, quartz has disappeared entirely, cummingtonite is replaced by green hornblende. No. 4 contains a considerable amount of sericite. However, this mineral must most probably be regarded as a product of secondary alteration of plagioclase, and it seems justifiable to propose the volume of sericite in the skarn rock to have been occupied by plagioclase at the original skarn formation. Next to the hornblende-plagioclase zone follows polymineralic skarn types; pyroxene, hornblende, epidote and anorthite being the dominating constituents. The proportions between the different minerals are so variable, however, that solitary volumetric analyses cannot give even an approximate conception of the composition.

The zonal arrangement in the series B shows very great similarities to the arrangement in the series A. The most conspicuous difference is that in B, no enrichment of biotite close to the cummingtonite-anorthite zone has been noted. The series C and D exemplify the zonal arrangement in chlorite-free cordierite-cummingtonite-quartzites. In these cases we also find a regular zone of hornblende and anorthite between the quartzites and the pyroxene- or epidote-rich skarn types, and furthermore the contents of cummingtonite and anorthite increase towards the hornblende zone. There is thus an apparent tendency for the cummingtonite-anorthite zone to result also in the chlorite-free quartzite. The conditions are illustrated in Fig. 16. The vertical lines (a, b, c etc. — i) represent 9 lines through a thin section as measured on a Leitz integration table. The lines run in parallel to the contact with the hornblende zone and are spaced 1 mm apart. Consequently the nine lines analysed answer to a zone 1 cm wide. The results disclose cordierite to successively decrease towards the hornblende-zone (cordierite being absent in the two

lines nearest to this zone), whereas anorthite, cummingtonite and also to a certain degree, quartz, increase. The horizontal broken lines indicate the composition of the quartzite at some distance from the hornblende zone (= No. 6).

In the series E and F in Fig. 15 the mineral composition of the »quartzitic» end members (Nos. 11 and 15) correspond to the cummingtonite-anorthite zone. In the rock specimens from which the thin sections Nos. 11 and 15 were obtained, this type of »quartzite» only was present, but only to a distance of 2—3 cm from the hornblende-zone. The »quartzite» may therefore represent a zone of alteration, somewhat wider than in the series A and B, occurring in normal cordierite- or biotite-chlorite-bearing quartzites. The series E and F may therefore be taken to elucidate merely the mineralogical changes from the cummingtonite-anorthite-zone to the hornblende-anorthite-zone.

The examples of zonal arrangement of different skarn minerals as given in Fig. 15 have been gained from rock specimens, where the zonal arrangement is megascopically conspicuous. However, veinlets of fairly pure hornblende-skarn are also found which border onto quartzites without any pronounced development of a hornblende-anorthite zone. In these cases, however, the rock bordering onto the hornblende skarn consists of practically pure cummingtonite. It thus seems to be as if the formation of pure hornblende-skarn is in each case, tied up with the fact that pure cummingtonite-skarn was formed previously.

On summing up all the alterations as indicated by the mineralogical changes from one zone to another and from the order of crystallization, as observed in thin sections, the following survey is obtained:

1.	Chlorite is replaced by or is consumed with the formation of biotite,	
2a.	Chlorite or biotite is replaced by or is consumed with the formation of cummingtonite,	
2b.	Cordierite	» » » » » » » » » cummingtonite,
3a.	Quartz	» » » » » » » » » anorthite,
3b.	Cordierite	» » » » » » » » » anorthite,
4a.	Cummingtonite	» » » » » » » » » hornblende,
4b.	Quartz	» » » » » » » » » hornblende,
4c.	Anorthite	» » » » » » » » » hornblende,
5a.	Hornblende	» » » » » » » » » pyroxene,
5b.	Anorthite	» » » » » » » » » pyroxene,
6a.	Pyroxene	» » » » » » » » » epidote,
6b.	Hornblende	» » » » » » » » » epidote,
6c.	Anorthite	» » » » » » » » » epidote.

The majority of the mineral changes exemplified in the table imply an addition of calcium in the newly-formed minerals. During this process, the proportions between the other constituents have changed more or less. It now lies before us to work out how the other components of the reactions were transported during the skarn-forming processes. The skarn formation proper can be regarded as being due to a migrating stream of Ca-ions proceeding from a fissure. The Ca-ions being fixed as a result of the formation of lime-silicates this stream gradually diminishes with increasing distance from the fissure. On that account there must be a decreasing concentration of added

Ca-ions with increasing distance from the fissure. In order to initiate a reaction between the added lime and the lime-free silicates a minimum concentration of Ca-ions is required. The consequences of the result would be the same if one considered the alterations to have been caused with the aid of solvents (cf. Goldschmidt (21)), or if, in accordance with Ramberg (24, 25) and Bugge (7), the process was considered to have taken place by diffusion in the solid state.

From a consideration of the zonal arrangement of the different skarn-minerals, it is obvious that the anorthite is the first lime-bearing mineral to be formed (in other words, it was formed at the lowest concentration of Ca-ions). A necessary condition, however, is that Al_2O_3 and SiO_2 are present in sufficient amounts in the pre-existing rock. Al_2O_3 is obviously taken from chlorite or cordierite, SiO_2 from the same minerals and further from quartz. The amounts of (Fe,Mg)O in cordierite or chlorite, which are liberated at the formation of anorthite at this stage of the mineralization, form, together with SiO_2 , cummingtonite. At a higher percentage of CaO, cummingtonite is no longer stable and is consequently transformed into hornblende. At still higher Ca-concentration, hornblende and anorthite are replaced by pyroxene, the Al-content of the two consumed minerals being taken up by the sulphide-bearing fluids and being fixed as a later phase of the mineralization in the form of epidote or zoisite.

The reactions between the minerals are quantitatively most clearly demonstrated in the two outer zones, the cummingtonite-anorthite-quartz zone and the hornblende-anorthite zone. In table 1 have been collected the changes in mineral composition between the different zones in the series, which are demonstrated in Fig. 15.

Table 1.
Survey of the variations of certain mineral percentages (given in vol.-%)
presented in Fig. 15.

Samples Nos.	Biotite Chlorite	Cumming- tonite	Quartz	Plagio- clase	Cordie- rite	Horn- blende	Magne- tite
1→3.....	— 41	+ 35	— 23	+ 21			— 2
10→9.....	— 27	+ 29	+ 1	± 0			— 2
6→6a ¹	+ 3	+ 16	+ 9	+ 25	— 44		+ 1
3→4.....		— 43	— 21	+ 2		+ 62	—
9→8.....	— 2	— 48	— 26	+ 15		+ 62	— 2
6a→5.....	— 4	— 54	— 18	+ 14		+ 66	— 6
11→12.....		— 50	—	— 10		+ 65	— 5
15→16.....		— 32	— 25	— 2		+ 60	— 1
6→5.....	— 1	— 38	— 8	+ 30	— 44	+ 66	— 5
14→13.....		— 48	— 22	+ 24	— 16	+ 62	—

¹ The sample No. 6a is the arithmetical mean of the two «cordierite-free» lines in Fig. 16.

The formation of anorthite and cummingtonite from chlorite and added lime can be expressed with the following formula, the composition of chlorite being chosen on the basis of its optical properties.

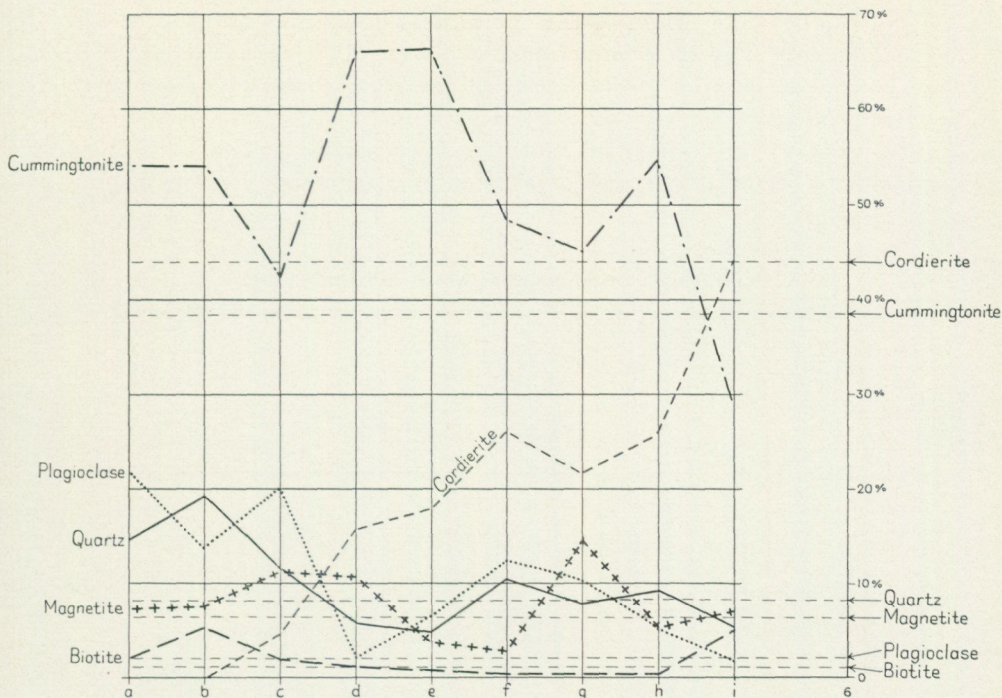
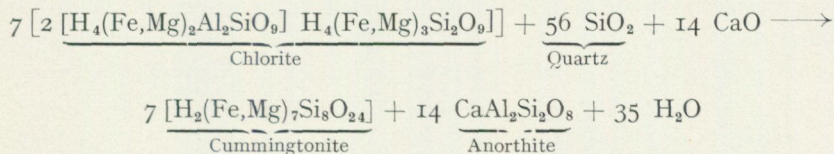


Fig. 16. The values of g measured lines in a thin-section carried out by means of the integration table. The lines a—i, run parallel with the boundary between the hornblende-anorthite zone (immediately to the left of the line a) and cordierite-cummingtonite quartzite (sample 6). The diagram represents in detail the transition from sample 6 to sample 5 in the series C in Fig. 15.



Analogously, approximate formulae can be written for the formation of cummingtonite and anorthite from cordierite + quartz and for the formation of hornblende + anorthite from chlorite or cordierite, cummingtonite and quartz. On account of the very complicated composition of chlorite and hornblende, these formulae become very clumsy to handle and so it may here suffice to supply merely the above example.

According to this formula, the reaction would, at a constant volume, lead to an increase of sp. gravity of only 1.5 %, which means that no noteworthy departure of materials excepting water, has taken place. In all the other reactions here discussed, the supply of substances is greater and consequently components other than water must have departed, the total volume being considered constant. If we calculate (according to the formulae) the proportions by weight for those minerals which are consumed and rebuilt during

the reactions, a comparison of the values thus obtained with those in table 1 and fig. 15 is possible. On account of the fact that chlorite or cordierite are completely consumed during the reactions, the amounts of these minerals are taken as unity for the sake of comparison.

The results are presented in Table 2 (all plagioclase has been calculated as anorthite, which in the present example is a permissible approximation):

Table 2.
Formation of the cummingtonite-anorthite zone.

	Consumed minerals		Newly-formed minerals	
	Chlorite + biotite	Quartz	Cummingtonite or antophyllite	Anorthite
According to reaction formula. . .	1	0.58	0.93	0.67
A. sample No. 1→sample No. 3 (acc. to volumetrical analyses)	1	0.54 (-)	0.99 (+)	0.58 —
B. sample No. 10→sample No. 9 (acc. to volumetrical analyses)	1	— 0.04 —	1.25 +	0 —
	Cordierite	Quartz	Cummingtonite	Anorthite
Acc. to reaction formula	1	0.13	0.37	0.95
C. sample No. 6—samples No. 6a ¹ (acc. to volumetrical analyses)	1	— 0.21 —	0.44 +	0.60 —

¹ Samples No. 6a is the arithmetical mean of the two cordierite-free lines in Fig. 16.

The table discloses that calculated mineral proportions in the series A coincide fairly well with the proportions as found from the thin sections, whereas in the series B and C, certain considerable differences appear. The symbols + and — respectively, found under the figures obtained from the thin sections, indicate as to whether these values are higher or lower than the values as calculated from the formulae. As will be seen, the same tendency is indicated in all these cases. In other words, more cummingtonite has been formed than was to be expected from the contents of (Fe,Mg)O in chlorite or cordierite, somewhat less anorthite than would be allowed from the Al₂O₃-content of chlorite or cordierite, and finally in A, a little less quartz and in B and C considerably less quartz, has been consumed than is indicated by the formulae.

Analogously, we can illustrate how theoretical values answer to those found in the thin sections at the formation of hornblende and anorthite from chlorite or cordierite, cummingtonite and quartz (Table 3).

We can not, of course, by these comparisons, expect to obtain a picture of the migrations of material which is correct in every detail. The theoretical values as well as those found empirically all suffer from comparatively considerable errors: The volumetric analyses are only within certain limits repre-

Table 3.
Formation of the hornblende-anorthite zone.

	Consumed minerals:			Newly-formed minerals:	
	Chlorite	Cummingtonite	Quartz	Hornblende	Anorthite
A. Sample No. 1→sample No. 4 (acc. reaction formula) ... (acc. volumetrical analyses)	1	0.23	0.79	1.93	0.33
	1	0.23	1.33 +	1.75 —	0.63 +
B. Sample No. 10→sample No. 8 (acc. reaction formula) ... (acc. volumetrical analyses)	1	0.76	0.85	2.78	0.20
	1	0.76	0.83 (—)	2.50 —	0.86 +
	Cordierite	Cummingtonite	Quartz	Hornblende	Anorthite
C. Sample No. 6→sample No. 5 (acc. reaction formula) ... (acc. volumetrical analyses)	1	1	0.31	2.14	0.59
	1	1	0.18 —	1.76 —	0.68 +

sentative of the rock-types, and the formulae also are approximate since certain minerals appearing in minor quantities, such as magnetite, zoisite etc., have not been considered. Certain general features can be illustrated by the tables, however. Hence we always find a minus sign below the anorthite-values at the formation of the cummingtonite-anorthite-zone but always a plus sign below the anorthite-values at the formation of the hornblende anorthite-zone. This means that that amount of Al_2O_3 from chlorite or cordierite not consumed at the formation of anorthite in the cummingtonite-zone has been used for the formation of more anorthite in the hornblende-zone than was to be expected from the formula. Analogously we always find the sign + below the cummingtonite-values at the formation of the cummingtonite, and always the sign — below the hornblende-values at the formation of the hornblende-zone. That is, a certain concentration of (Fe,Mg)O in the cummingtonite-zone is compensated for by a deficiency of (Fe,Mg)O in the hornblende-zone. In other words: The two reaction zones in question tend to balance between themselves the content of iron, magnesium and aluminium of the pre-existing rock.

On the other hand, as only comparatively few stable minerals exist within the two reaction zones, their composition is fairly uniform. The mineral proportions of the hornblende-anorthite-zone are particularly noteworthy. The proportions between hornblende and plagioclase are in the six series in fig. 15 as follows: 67 : 33, 61 : 39, 67 : 33, 67 : 33, 65 : 35, 67 : 33, that is, approximately 2 : 1. The quite good agreement between the various values is the more remarkable since the hornblende zones in question border on rocks which are mineralogically and in certain respects chemically, different.

the analyses plotted in the diagram, Fig. 12, the gradual introduction of lime is seen to be conspicuous. The lime running from the points I and II towards the CaO-corner denotes the composition of rocks with constant proportions of $(\text{Fe,Mg})\text{O} : (\text{Al,Fe})_2\text{O}_3$ but with varying amounts of CaO. The results obtained by volumetric analyses are confirmed, e. g. the cummingtonite-anorthite zone and the hornblende-anorthite zone have developed with approximately constant $(\text{Al,Fe})_2\text{O}_3 : (\text{Fe,Mg})\text{O}$ -proportions. When discussing the inter-mineralogical reactions on the basis of volumetric analyses of thin sections, we discerned a tendency towards a concentration of $(\text{Mg,Fe})\text{O}$ in the cummingtonite-zone and of Al_2O_3 in the hornblende-zone. This tendency is not clearly indicated by Fig. 17, but we must remember that the volumetric analyses refer to a considerably smaller quantity of rock than do the chemical analyses. The latter therefore illustrate the main features of the mineralization, the discussion based on the thin section values only being meant to elucidate the details in the variations from one zone to another. In Fig. 17 a conspicuous metamorphic differentiation between Al-rich and Fe-Mg-rich skarn types is first expressed as the development of pure hornblende, pyroxene or epidote masses.

We shall now consider certain quotients which could not be presented in the diagram. From the analyses the following quotients have been calculated:

Table 4.

Analysis No.	100·MgO	100·MgO	100·MgO	100·(Fe, Mn)O	100·Al ₂ O ₃	100·FeO
	(Mg,Fe,Mn) O	(Mg,Fe,Mn)O + 2 Fe ₂ O ₃	MgO + Al ₂ O ₃	(Fe,Mn) O + Al ₂ O ₃	(Al,Fe) ₂ O ₃	FeO + Fe ₂ O ₃
I.....	45.5	40.5	56	60	84.5	89
II.....	45.5	43.5	52	56.5	95.5	96.5
VI.....	51	49.5	53.5	52.5	97	97.5
VII.....	58.5	54	56.5	48	91	90.5
VIII....	62	55.5	83.5	75.5	67.5	86.5
IX.....	62	57	91	81	62	89.5
III.....	36.5	33	51	65	90	94
IV.....	36	25.5	47	59	69	77

The variations of the proportions, iron : magnesium at the different stages of the skarn mineralization are particularly interesting. Whether divalent iron only be considered (1st column) or also the total iron-content (2nd column), as represented in the analyses it becomes quite clear, that during the skarn forming process, the Mg : Fe ratio tends towards a more magnesium-rich value. The change is discernible even in the cummingtonite-zone and grows more conspicuous in the hornblende and pyroxene zones. Consequently we can conclude that the skarn mineralization leads to a »driving out» of more iron than magnesia from the replaced rock portions.

During the description of the various quartzite rocks it was mentioned that garnet- and magnetite-bearing quartzites appear outside the skarn areas but in their immediate vicinity, and that they chemically represent types with higher iron-contents than the normal quartzites. These chemical

differences are visualized by comparing the iron-magnesium-quotients of the analyses Nos. I and II with Nos. III and IV in Table 6, the two last mentioned rocks being conspicuously enriched in iron as compared with the normal types. At first sight, one could readily presume, that iron from the ore-bearing fluids diffused away from the channel-ways into the surrounding rock, the remaining iron of the fluid being later combined in sulphides. However, experiences from the relation between skarn mineralization and sulphide mineralization give the formation of almandite and magnetite in the outer regions another aspect. The skarn rocks which are more closely associated with the sulphides than are the almandite- and magnetite-bearing quartzites, are characterized by an extraction of iron as compared with the »normal» quartzites. It is therefore very improbable that the ore-bearing fluids should be the source of the iron needed for a formation of almandite or magnetite in the quartzites. Pyroxene and hornblende being by far the most dominating minerals in the skarn masses, a likely assumption is *that the formation of almandite and magnetite in quartzites surrounding the skarn masses has originated through a supply of iron from portions replaced during the Ca-metasomatism.*

The ratios of $\text{MgO} : \text{Al}_2\text{O}_3$ are presented in the third column of Table 4. As can be observed, these ratios vary within narrow limits, even as far as the hornblende-anorthite-zone. As opposed to this, the ratios for $\text{FeO} : \text{Al}_2\text{O}_3$ evidence a successive tendency to decrease even throughout the cumingtonite-zone and the hornblende-anorthite-zone. (4th column in Table 4.) Thus, a more intense removal of Fe as compared with Mg is indicated, but this tendency is still too weak to be conspicuous in Fig. 17. From Table 4, it becomes apparent that the $\text{Mg}^{2+} : \text{Al}^{3+}$ -ratios in the series of analyses, I, II, VI and VII are those which are most constant (in the first four columns). The constancy of the $\text{Mg}^{2+} : \text{Al}^{3+}$ -ratio supplies a clue in the explanation of the above-mentioned, very constant mineral proportions of the hornblende-anorthite zone from case to case (see p. 35): The formation of skarn minerals in this zone has occurred in such a way that the $\text{Mg}^{2+} : \text{Al}^{3+}$ -ratio of the original rock has been retained. Only after the skarn mineralization has progressed still further, i. e. when even anorthite becomes unstable and is replaced by hornblende or pyroxene, does a metamorphic differentiation between Mg and Al become noticeable on a larger scale.

The values in the two last columns which reflect the variations in firstly the $\text{Al}^{3+} : \text{Fe}^{3+}$ -ratio and secondly in the degree of oxidation, give no further information about the process of skarn formation.

Of the constituents which provide essential ingredients in the rocks in question, SiO_2 has not as yet been mentioned. Fig. 18 shows the proportions between SiO_2 , $(\text{Mg,Fe})\text{O}$ and $(\text{Al,Fe})_2\text{O}_3$ in the analyses I—IX. Analysis No. V, which represents the andalusite-bearing muscovite-quartzite from Lappliden, is of no interest in the above connection. The remaining analyses all fall within a relatively narrow SiO_2 range (skarn as well as quartzite analyses) and pure epidote is also seen to be within this range.

From the facts mentioned above it seems most probable, that the skarn

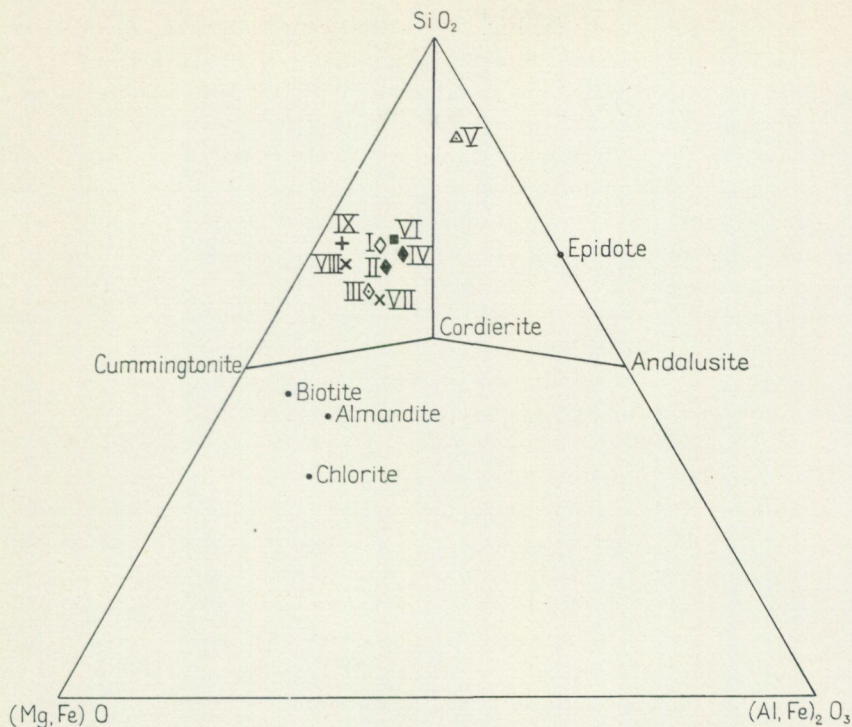


Fig. 18. The analyses of quartzites and skarn-rocks projected in a SiO_2 — $(\text{Mg,Fe})\text{O}$ — $(\text{Al,Fe})_2\text{O}_3$ triangle.

mineralization was brought about by a supply of Ca, other elements in the mineralizing solutions being practically of no importance. The skarn minerals were formed by reactions between the added Ca ions and the indigenous silica, iron, magnesium and aluminium content of the quartzites, and the proportions between these elements were regulated by the formation of the most stable mineral association for various concentration intervals of Ca^{2+} .

The minerals of the skarn parageneses suggest P-T-conditions corresponding to amphibolite facies and epidote-amphibolite facies. The minerals diopside, andradite, anorthite, hornblende and cummingtonite are all common in amphibolite facies. Sericite-(amphodelite-)building must be regarded as a later alteration-process which has come to pass under conditions other than those of the skarn formation proper. Sericite is thus, in all surety, a hystero-genous mineral, in accordance with Eskola's definition (6, p. 341). It is more difficult to give a direct utterance on the position occupied by epidote. The formation of epidote is so closely tied up with the skarn-building in general, that it is a matter of difficulty to consider it as having been formed under P-T-conditions essentially different from those of the skarn-rocks as a whole. Generally speaking, the mineral parageneses in question correspond to the subdivision in the A-C-F triangle given by Barth for the epidote-amphibolite

facies in Southern Norway (3, Fig. 15) — that concerning the lime-rich parageneses below the line anorthite-cummingtonite. On the other side of the mentioned line, the fields correspond entirely to the amphibolite facies of Eskola for parageneses with excess Al_2O_3 (6, Fig. 55). Ramberg (23, p. 139) and Rosenqvist (27, p. 111) have, however, by their studies in Norway come to the conclusion that epidote can occur as a stable mineral, in the same mineral facies as diopside and cummingtonite. This being true, epidote might appear as a stable mineral associated with the other skarn minerals as found in the Adak parageneses.

Now, it is not uncommon to find epidote in the same thin section as anorthite and diopside (as well as hornblende). A glance at the diagram, Fig. 17, discloses that according to the grouping there given to the oxides, this cannot be a stable association (other than for very special compositions).

The line connecting epidote and hornblende separates anorthite and diopside, and only for those compositions which fall on this line is it reasonable to expect anorthite, epidote and hornblende together. The objection could here be raised that since Fe^{3+} and Al^{3+} are not able to substitute each other in anorthite, then in the presence of epidote, one must reckon with a four-component system [Al_2O_3 , Fe_2O_3 , CaO and $(\text{Mg,Fe})\text{O}$], and epidote should thereby theoretically represent a stable component. However, the microscopical results clearly show that epidote replaces both anorthite and diopside and it seems therefore quite probable, that the skarn-forming process embraces a temperature interval in which, under higher temperatures, epidote is unstable (the lines, diopside-epidote-hornblende in Fig. 17 should then be replaced by the line, diopside-anorthite), while at lower temperatures, epidote is formed at the expense of anorthite and diopside. (It seems probable that anorthite is unable to exist as a stable component at the stage where epidote is formed.) In summarized form, the fact can be established that the formation of the skarn minerals has occurred under P-T-conditions which most nearly correspond to the transition between the amphibolite facies and the epidote-amphibolite facies.

On the « Al_2O_3 -side» of the anorthite-cummingtonite line, it is not possible to characterize, to any closer degree, the mineral facies of the skarn-forming process. It is obvious, that anorthite-cummingtonite constitute a stable mineral association. The stability of chlorite in quartzite-parageneses has been dealt with earlier and everything indicates that the mineral is not stable during the skarn mineralization process. In this respect, an indicative point is that chlorite is very easily altered even in the weakest stage of the skarn mineralization. In those cases where a sufficient amount of potash is available, chlorite is transformed to biotite, as is indicated by sample 2 in case A, Fig. 15.

In a discussion of the mineral facies of the skarn parageneses, a further factor must be considered, namely, the variations of the ratio $\text{Fe}^{2+} : \text{Mg}^{2+}$, this being of considerable importance. As has already been mentioned, Eskola, in his first statement of mineral facies, gave prominence to the fact that almandite can occur as a stable component under P-T-conditions where pyrope-richer garnets are yet unstable. In an analogous fashion, it has become ap-

parent that in several mineral groups in which far-reaching substitution can take place, there are certain ranges in the proportions between the substituting elements, which are characteristic for certain facies. These points of view have been recently discussed by Ramberg (24). It could now readily be considered that the displacement in the MgO : FeO-ratio found in the Adak skarn parageneses as compared with that of the quartzites, is due to the formation of pyroxenes and hornblende with their Fe : Mg-proportions lying within a certain range of variation, these proportions being characteristic for the most stable forms under the P-T-conditions prevailing during the mineralization.

The conditions at the mineral formation deviate perhaps, to a certain degree, from those present during a normal regional metamorphism. The foremost difference seems to rest in the »time-factor» at the formation of lime-silicates. During regional metamorphism, the process is characterized by slow, continuous changes of temperature and pressure, which give rise to reactions accompanied by a transfer of substances. At the Adak Mine, skarn formation has been brought about by a comparatively sudden change in the chemical composition (and perhaps even of the temperature).

A diffusion of Ca ions from certain channel-ways implies that a fall most probably occurs in the Ca^{2+} -concentration from the channel-ways towards the uninfluenced quartzite. The composition of the skarn minerals and mineral associations would then be expected to be controlled by the proportions in the quartzites of the elements needed for the skarn formation, and by the concentration of Ca-ions supplied, this latter being dependent on the distance from the channel-ways.

If, however, the composition of the newly-formed lime-silicates has a limited range of variation, certain of the constituents in the quartzite will be mobilized to a greater degree than others.

Inasmuch as an increase in the Ca^{2+} -concentration beyond a certain limiting-value can cause a mineral, stable at an earlier stage of the skarn mineralization, to become suddenly unstable, a sudden displacement in the CaO content of the newly-formed mineral association can occur (as, for example, between the cummingtonite zone and the hornblende zone). That the above given statements hold, is demonstrated by the fact that the boundary between different skarn-zones is often particularly sharp. We could expect, for example, that the transition between the cummingtonite zone and the pyroxene zone, should be represented by stable mineral associations, anorthite, cummingtonite and hornblende appearing together and hornblende successively replacing cummingtonite towards the pyroxene zone and with a similar successive change-over from the hornblende zone to the pyroxene zone. The assumption that the boundary between the different skarn zones is caused by the Ca^{2+} -concentration exceeding a certain limiting-value, characteristic for each of the newly-formed mineral assemblages, implies that a curve representing the Ca^{2+} diffusion into the quartzite possesses, in all probability, an even gradient, whereas that represented by the skarn zones displays sudden changes in the CaO content.

The evolution of the skarn mineralization may be summarised as follows. The first sign of a formation of lime-silicates is the appearance of anorthite, the FeO and MgO in the quartzite being bound up as cummingtonite. When the Ca^{2+} concentration exceeds a certain limiting-value, cummingtonite is no longer stable; hornblende replaces cummingtonite, anorthite is still stable. The $\text{Mg}^{2+} : \text{Al}^{3+}$ quotient of the quartzites is, generally speaking, retained in both phases during the reaction. Since cummingtonite and hornblende in particular, require a higher quotient of $\text{Mg}^{2+} : \text{Fe}^{2+}$ than that of the original rock, a portion of the iron will be mobilised. Still higher content of Ca^{2+} results in that anorthite also becomes unstable, being replaced by hornblende or more often, by diopside. This change requires a further loss of Fe^{2+} to occur, but also leads to the mobilization of Al^{3+} , which, in combination with trivalent iron, gives epidote. The final observable stage of mineralization with sinking temperature is sericitisation, and the appearance of calcite and epidote, or sometimes hornblende, as crystals along open fissures. The iron mobilized at the skarn mineralization is, for the most part, driven out into the surrounding quartzites, there to give rise to the formation of almandite or magnetite. This whole development can be said to supply a very fine example of metamorphic differentiation — in this case, brought about by the introduction into the rocks of a foreign constituent, lime. In the general terminology for metamorphic differentiation, as applied by Eskola (13), it can be said that it is quite clearly regulated by »the principle of enrichment of the stablest constituents».

Comparisons and some petrogenetical consequences.

In the introduction it was mentioned that reactions between lime-bearing and siliceous rocks have drawn a considerable interest in petrology, and that the literature is quite richly stocked with comparative material. Within regionally metamorphic areas characterized by amphibolite facies or epidote-amphibolite facies, the development of diopside-skarn along contacts of limestones is of common occurrence and inasmuch as the siliceous rocks contain biotite or chlorite in association with quartz, a zone occurs between the diopside-skarn and the siliceous rock, in which hornblende replaces diopside (cf. Eskola 6, p. 342). In the Adak Mine, skarn occurs which apparently represents calcareous beds in a primary layered rock sequence. The minerals in such skarn-bands are, generally considered, the same as those already described; but the zoning is less apparent and in those cases where zoning is discernible, the zones are only a few mm thick. At the Lindsköld Mine, ca. 300 m N of the Adak Mine, lime-silicate accumulations occur within layered rocks, which are only slightly affected by the metasomatism leading to the quartzites and which overlie the quartzites. These skarn-accumulations are, for the most part, composed of a light-green to white diopside, clinozoisite, anorthite and often grossularite. The following zonal arrangement from the skarn mass towards the siliceous rock is generally found: A band of about 2 mm thickness,

which consists almost entirely of diopside, borders the complex skarn mass and outside of this band, a 1 mm thick band of hornblende, plagioclase and quartz occurs. Cummingtonite is absent; however, the siliceous rocks are here of another composition than at the Adak Mine and consist of anorthite-rich plagioclase, biotite and quartz in the cases examined. As may readily be seen, the reaction-zones in these examples are very narrow as compared with those described below from the Adak Mine, where the skarn-formation results from a supply of lime in connection with sulphide mineralization.

Particularly regular and informative zones are formed when eruptive sialic rocks intrude limestones, many such cases having been extensively discussed in the petrological literature. Hereunder, will be discussed a few examples in which chemical and mineralogical data supply a possibility for numerical comparisons with the skarn rocks of the Adak Mine.

Von Eckermann's investigations of the mineral parageneses at Mansjön and Tennberget are of a particularly illuminative nature. In both these cases, it is a question of skarn-formation at the contacts between granite or pegmatite and limestone. Von Eckermann has discussed in detail the evolution of the mineral-building, so that it will suffice here to mention just a few of the points which are of special interest in the comparison with the skarn-zoning at the Adak Mine. From the analyses published in the Tennberget paper, which serve to illustrate the chemical variations from limestone to granite the Fe : Mg-ratios have been calculated. These are presented in Table 5, which also demonstrates the most essential features in the mineral zoning in its most complete development.

Table 5.

	100 MgO (Mg,Mn,Fe)O	100 MgO (Mg,Mn,Fe) O + 2 Fe ₂ O ₃
Granite 240 m from the contact	41	21
» 75 » » »	40	23
» 5 » » »	40	29
» at » »	51	42
Diopside-bearing quartz-plagioclase rock	27	26
Garnet	19	10
Vesuvianite (outer zone).....	69	65
» (middle zone)	62	49
» (innermost zone).....	52	39
Diopside	62	62
Wollastonite		
Light diopside in limestone	70	
Dark diopside in limestone	33	

The presentation represents a section from a normal granite to a normal limestone. The various skarn-zones are not usually monomineralic and consequently the tabulation merely reproduces the most characteristic minerals for the various zones. The boundary between »contaminated granite» and »skarn-mineralized limestone» runs between »diopside-bearing quartz-plagioclase rock» and »garnet». Here we find a sudden change in the proportions

of the components, which represent the greatest contrasts between limestone and granite, namely CaO and SiO₂. The two diopside varieties given at the bottom of the table are such as are met with as sporadic »contaminations» in the limestone proper.

If this skarn-zoning be compared with the skarn-zones at the Adak Mine, both agreement as well as disagreement is found: On first sight, the impression is conveyed that the hornblende-zone of the Adak Mine is missing. However, the normal granite is a biotite-chlorite-bearing type, which in the direction of the contact with the limestone, passes over into a hornblende-granite (the two first analyses of granite in the table are hornblende-free, whereas both the latter are hornblende-bearing). Thus the zone corresponding to the hornblende-zone at Tennberget is found displaced into the granite itself.

Diopside occurs again as an inner zone which represents enrichment of iron and magnesium in relation to aluminium. Whilst the Al₂O₃-content of the Adak skarn rocks is tied up chiefly in epidote, it is within the Tennberget parageneses, bound in the grossularite- and vesuvianite-zones situated between the pyroxene-zone and the more siliceous rocks. This fact, along with the occurrence of wollastonite, partially as a zone nearest the pure limestone, suggests that the Tennberget parageneses were formed at higher temperatures than were the Adak parageneses.

A point of particular interest is that the Fe:Mg-ratios in those zones which are comparable with those of the Adak Mine, vary in the same manner as at the Adak Mine, i. e. towards a higher Mg:Fe ratio, from the siliceous to the calcareous end of the system. The diopside of the inner skarn-zone and the pale diopside in the limestone show the values 62 and 70, respectively, for the ratio $\frac{100 \text{ MgO}}{(\text{Mg, Fe, Mn})\text{O}}$ while the normal granite displays a value of 41. An exception from the above-mentioned tendency is indicated by the diopside of the plagioclase-quartz-zone, nearest the garnet-zone, a value of 0.27 being found. Here, however, both the FeO content as well as the MgO content are considerably lower than in the granite itself — this zone obviously represents that portion of granite where the most intensive extraction of materials for the skarn formation of the limestone has taken place. Although the dominant component of the garnets is grossularite, the garnet-zone represents the strongest absolute iron-enrichment among the existing skarn-minerals (2.35 % FeO and 8.52 % Fe₂O₃). Thus it seems as if on the formation of the skarn parageneses, the excess of FeO over MgO, which must be assumed to have resulted due to the formation of pyroxene (and hornblende), was locked up in the garnet-zone (although to a considerable degree as trivalent iron).

Concerning the iron-richer diopside in the limestone, $\left(\frac{100 \text{ MgO}}{(\text{Mg, Fe, Mn})\text{O}} = 33 \right)$, von Eckermann emphasizes that this was formed at a later stage and at lower temperatures than the other skarn minerals, thus representing a lower-temperated mineral facies. This postulation is strengthened also by the association of maganiferous garnet with iron-rich diopside.

At Mansjön, pegmatite dykes appear in limestone and along these pegmatites a zoning is found. Phlogopite constitutes the zone nearest the limestone, thereafter follow pure pyroxene, pyroxene + scapolite, scapolite + quartz and finally, scapolite + plagioclase + quartz. In this case, magnesium and aluminium are enriched in the innermost zone in the form of mica. The diopside of the contact-zone has a $\frac{100 \text{ MgO}}{(\text{Mg,Fe,Mn})\text{O}}$ -value of 66; the value in a diopside, 1 cm from the contact, being 88.

Adams and Barlow, working in an Archean area in Canada, have by description and analyses, illustrated the formation of amphibolitic rocks by reaction between limestone and granite. Three rock analyses representing different stages of transition between limestone and granite are presented (1. p. 104): Pyroxene + calcite + plagioclase — plagioclase + some scapolite + hornblende + pyroxene — hornblende + plagioclase + some pyroxene. The values for $\frac{100 \text{ MgO}}{(\text{Mg,Fe,Mn})\text{O}}$ in these three analyses are respectively 71—60—59, whilst the corresponding values of the surrounding granite, taken from two analyses, were found to be 42 and 35. The Fe : Mg-quotient is thus displaced towards the lime-richer members in the same way as in the earlier cases.

From Baneheia, north of Kristiansand in Norway, Barth has described skarn-formation in connection with regional metamorphism and under P-T-conditions leading to mineral associations corresponding to epidote-amphibolite facies (3, 4). Regular, zonal enrichment of the various lime-silicates is often found to have developed: diopside + scapolite — hornblende + scapolite — hornblende + plagioclase. In an analysis of the amphibolitic type, the proportions MgO : (Fe,Mn)O were found to be 59 : 41 (in the hornblende, 60 : 40). On the basis of the refraction, the corresponding proportions in diopside were evaluated as 57 : 43.

In his work on the metamorphism of palaeozoic sediments in the Dutchess County, New York, Barth supplies yet further examples of gradually developing skarn-formation during regional metamorphism (5). The analyses, Nos. 8 and 17, in this description represent inclusions of slate in dolomite, these both representing approximately the same degree of metamorphism. Analysis No. 8 is of a hornblende-free rock, No. 17 of a hornblende-bearing rock.

$\frac{100 \text{ MgO}}{(\text{Mg,Fe,Mn})\text{O}}$ for analysis 8 = 50, for analysis 17 = 59. To what degree both these values may be regarded as characteristic for a continually proceeding skarn mineralization of a homogeneous material is, however, unsure. The variations in the $\text{Fe}^{2+} : \text{Mg}^{2+}$ -ratios within the normal, low-metamorphic schists are, according to several analyses of schists from this region, considerable, and both Mg-rich as well as the Fe-rich types occur.

In connection with the two examples from Barth's investigations, another fact must also be considered. In both of these cases, the altered carbonate-rock was a dolomite and therefore an increase in the Mg : Fe-ratio of the skarn minerals from the siliceous towards the calcareous members was to be expected.

According to Barth, mainly SiO_2 and FeO were added to the carbonates and only to a lesser degree, MgO and Al_2O_3 .

In many of the above mentioned examples the mineral associations and their development are in several respects not directly comparable with these of the Adak Mine, but there remains the noteworthy fact that for pyroxene skarn and, to a certain degree, for hornblende skarn also, the values of the quotients $\frac{100 \text{ MgO}}{(\text{Mg,Fe,Mn})\text{O}}$ vary within relatively narrow limits (generally 60—65). This could be interpreted in the following manner. Within the range of temperature and pressure prevalent during the mineral-forming processes here discussed, amphiboles and pyroxenes tend to attain a certain $\text{Mg} : \text{Fe}$ -ratio, in which the $\text{Fe} : \text{Mg}$ -quotients of reacting components do not play any decisive part. Approximately the same displacement of the $\text{FeO} : \text{MgO}$ -ratio from the siliceous rocks to the calcareous rocks occurs, the latter being either Mg -rich (e. g. dolomites) or Mg -free (pure limestones). As a result of this, »streams» of ions diffusing towards and into a calcareous rock may vary widely in composition from case to case — in one case, more Mg^{2+} than Fe^{2+} wanders towards the limestone, in the other case, chiefly Fe^{2+} wanders out (in a dolomite).

Several of the examples presented seem to indicate that in the Fe - Mg -bearing silicates, the $\text{MgO} : \text{FeO}$ -ratios of the silicates have been displaced in the direction of more Mg -rich values when lime-richer minerals are formed under approximately constant temperatures and pressures. This tendency has earlier been brought to light, in very tangible form, by Eskola (12, p. 279), in a description of the contact phenomena between gneisses and limestone in Massachusetts. A metasomatic alteration under conditions of approximately constant temperature and pressure, at which e. g. the iron-magnesium content of the biotite is consumed during formation, firstly of hornblende and then of pyroxene, ought thus to show a tendency to be attended contemporaneously by a certain separation between FeO and MgO . However, Eskola's results indicate that the $\text{FeO} : \text{MgO}$ -ratio is also dependent on the ratio of femic to salic minerals in the rocks: the higher the content of femic minerals, the higher is also the $\text{MgO} : \text{FeO}$ -ratio in these minerals. This intimates that the concentration of salic elements is also a factor of importance for the stability of the Fe - Mg -bearing silicates. Regarding, for example, the unexpectedly high iron-content in diopside from the quartz-plagioclase zone from Tennberget, this is in accordance with Eskola's empirically derived rule, inasmuch as the diopside of the rocks in question plays quantitatively, a very subordinate rôle, as compared with quartz and plagioclase.

Considering metasomatic processes in general the enrichment of the most stable components, in accordance with Eskola's definition (13) is of course a factor of great importance and is moreover, a consequence of the prevailing conceptions of metasomatic processes. It seems, however, as if certain minerals and mineral combinations display such a degree of stability that they are apt to be formed even under circumstances leading to a mobilization of those elements which find no place in the stable associations. That is to say,

such reactions give rise to a »secondary» transfer of substances, possibly attended by further metasomatic exchange. If the »most stable minerals» and »mineral-associations» in various mineral facies and within various ranges of concentration for *certain* components (for example, CaO in the cases here discussed) could be empirically established than an explanation might be forthcoming as to many problems concerning the exchange of elements as well as the source of these elements during metamorphism.

Backlund (2) has made an interesting investigation of the relative rates of diffusion of the different ions during skarn-formation within the Tennberget and Mansjö areas (grounded on the analyses published by von Eckermann) and found that the following order is applicable for diminishing rate of diffusion from the granite into the limestone: Si—Al Na—K. Roughly speaking, this arrangement corresponds to the wollastonite-zone; the vesuvianite and andradite-zones; hornblende granite. The pyroxene-zone, between the wollastonite- and vesuvianite-zones, suggests to a certain degree, that Fe and Mg should, in this case, be placed between Si and Al. That Si stands here as one of the end-members and so to say, is able to wander past Fe and Mg depends on the fact that the P-T-conditions for wollastonite-formation are realized. At lower temperatures when wollastonite can no longer result, Si^{4+} does not migrate further than Fe^{2+} and Mg^{2+} . No traces have ever been found, for example, of a quartz-calcite-zone inside of the pyroxene-zone in parageneses characteristic of epidote-amphibolite facies. The occurrence of epidote in the innermost zones at the Adak Mine shows that under these prescribed P-T conditions, Al diffuses further than Fe and Mg.

A particularly instructive example of metamorphic differentiation through enrichment of the most stable minerals has been rendered by Magnusson in the description of the mineral parageneses at Långban, namely, the formation of a biotite-rock (»sköl») at the boundary between pyroxene-amphibole-bearing skarn and leptite (22, Figs. 41 and 42). Magnusson has shown that the material which has produced the biotite comes partially from leptite and partially out of the adjacent normal skarn, H_2O being the only externally acquired component. SiO_2 , Al_2O_3 as well as $(\text{Na},\text{K})_2\text{O}$ have been removed from the leptite, the removal of alkalies having been greater than the removal of Al_2O_3 . This leads to the production of a transition zone with cordierite and andalusite between the leptite and the biotite-rock. From the hornblende-pyroxene skarn the biotite-rock has acquired $(\text{Fe},\text{Mn},\text{Mg})\text{O}$ along with a little CaO. Between the normal skarn and the biotite-rock proper, a transition zone occurs in which biotite, hornblende, epidote, feldspar and scapolite are the main constituents. It is now of considerable interest to establish the fact that although the contrasts between the main rocks — skarn and leptite — are roughly the same, chemically and mineralogically, as in several of the cases cited earlier, the mineral-zoning and the transfer of substances are, to a considerable degree, of an entirely different character. One of the most striking dissimilarities with, for example, Tennberget is that during the formation of the biotite-rock, the alkalies display a relatively greater diffusion-ability than does Al.

Table
Analyses of Secondary quart-

Analysis No.	I		II		III		IV	
	%	mol.-prop.	%	mol.-prop.	%	mol.-prop.	%	mol.-prop.
SiO ₂	57.57	9 585	57.77	9 619	53.46	8 901	57.48	9 570
Al ₂ O ₃	11.74	1 152	15.62	1 532	14.44	1 417	12.63	1 239
Fe ₂ O ₃	3.33	209	1.18	74	2.55	160	8.78	550
FeO	12.70	1 768	14.31	1 992	18.91	2 632	13.50	1 879
MgO	5.85	1 481	6.62	1 642	6.02	1 493	4.41	1 094
CaO	1.55	276	0.82	146	1.00	178	0.38	68
Na ₂ O	0.11	18	0.00	0	0.22	36	0.27	44
K ₂ O	0.67	71	0.49	52	0.27	29	0.10	11
H ₂ O ⁺¹¹⁰	4.81	2 670	2.21	1 227	1.67	927	1.50	833
TiO ₂	0.96	150	0.74	93	0.77	96	0.33	41
MnO	0.09	13	0.08	11	0.13	18	0.11	16
P ₂ O ₅	0.17	12	0.07	5	0.17	12	0.15	11
CO ₂	0.03	7	0.08	18	0.05	11	0.08	18
F	0.17	90	0.07	37	0.08	42	0.06	32
S	0.14	44	0.06	19	0.12	37	0.20	62
Cu	—	—	—	—	—	—	—	—
H ₂ O ⁻¹¹⁰	0.17	—	0.04	—	0.11	—	0.13	—
Total	100.06		100.16		99.97		100.11	
O subtracted for F	0.07		0.03		0.03		0.03	
O subtracted for S	0.07		0.03		0.06		0.10	
Total	99.92		100.10		99.88		99.98	
Niggli-values								
Si	187		175		147		179	
al	22.5		28		23		23	
c	5.5		2.5		3		1	
fm	70.5		68.5		73		75	
alk	1.5		1		1		1	
mg	0.42		0.44		0.30		0.27	
k	0.80		1.00		0.45		0.20	
o	0.13		0.04		0.08		0.37	

¹ S here bound in pyrite.

	Analyst
Analysis I: Chlorite-quartzite Adak Mine, 80 m level, drill-hole 16; 49.71—50.43 m	F. Swenberg, Geol. survey of Sweden.
Analysis II: Cordierite-quartzite, Adak Mine, 80 m level, drill-hole 16; 51.02—52.03 m	— » —
Analysis III: Cordierite-garnet-quartzite Adak Mine, 80 m level, drill-hole 16; 52.23—53.16 m	— » —
Analysis IV: Magnetite-rich quartzite. Adak Mine, drill-hole 7; 59.65—60.24 m	— » —

The root of these divergencies may be sought in the particular condition that in the referred-to case at Långban, the dominating stability of the biotite is the decisive factor. The biotite-building process can be regarded as the tendency towards the attainment of an equilibrium within a system including leptites as well as skarn, and this process causes a mobilization of those elements necessary for the formation of biotite.

6.

zites, and skarn rocks.

V		VI		VII		VIII		IX	
%	mol.-prop.	%	mol.-prop.	%	mol.-prop.	%	mol.-prop.	%	mol.-prop.
68.64	11 429	54.25	9 033	46.34	7 716	52.86	8 801	51.44	8 565
12.92	1 267	13.81	1 385	15.33	1 504	4.87	478	3.03	297
2.21	138	0.66	41	2.11	132	3.65	229	2.52	161
6.20	863	13.89	1 934	11.32	1 576	13.34	1 857	9.79	1 363
1.04	258	6.29	1 560	7.75	1 922	9.68	2 401	8.46	2 098
0.98	175	6.06	1 081	12.79	2 281	10.06	1 794	22.88	4 080
0.23	37	0.42	68	0.40	65	0.67	108	0.26	42
0.99	105	0.10	11	0.22	23	0.18	19	0.11	12
4.15	2 304	1.81	1 005	1.82	1 005	2.42	1 343	0.49	272
0.32	40	0.55	86	0.61	96	0.29	0.45	0.14	18
0.05	7	0.38	58	0.19	27	0.27	38	0.26	37
0.14	10	0.08	6	0.06	4				
0.03	7	0.12	27	0.16	41	0.06	14	0.17	39
0.12	63	0.38	100	0.18	95	1.02	537	0.37	195
1.76	549	1.37	427	0.65	203	1.08	337	0.64	200
		0.48	76	0.11	17	0.08	13		
0.20		0.07		0.08		0.05		0.17	
99.98		100.72		100.12		100.58		100.73	
0.05		0.16		0.08		0.43		0.16	
10.44		0.57		0.27		0.50		0.32	
99.49		99.99		99.77		99.68		100.25	
412		147		101		131		104	
45.5		22.5		19.5		7		3.5	
6.5		17.5		30		27		49.5	
43		59		49.5		64		46.3	
5		1		1		2		0.7	
0.22		0.43		0.51		0.55		0.55	
0.74		0.14		0.14		0.15		0.21	
0.23		0.02		0.07		0.11		0.09	

		Analyst
Analysis V:	Muscovite-quartzite, Lappliden, drill-hole 2; 25.43—29.84 m	F. Swenberg, Geol. survey of Sweden.
Analysis VI:	Cummingtonite-anorthite-quartzite, Adak Mine, 165 m level	— » —
Analysis VII:	Hornblende-anorthite-skarn, Adak Mine, 165 m level	— » —
Analysis VIII:	Hornblende-skarn, Adak, Mine, 165 m level	Aino Balder, — » —
Analysis IX:	Pyroxene-skarn, Adak Mine, 165 m level	F. Swenberg, — » —
		— » —

Further examples of metamorphic differentiation and migration of substances caused by the formation of particularly »stable» minerals or mineral-associations characteristic for certain P-T-conditions could be presented. In greenschist facies for example, chloritic rocks are considerably frequent as has been emphasized by Eskola, and Vogt showed by the treatment of the metamorphism within the Sulitelma area, that gabbros in the lowest temperatured

facies tended to pass over into chloritic schists, a loss of lime then taking place (35). The appearance of chlorite and sericite in more or less monomineralic masses in connection with the formation of sulphide ores can also be mentioned. In this last-mentioned case, very similar final products arise even if the original rocks were chemically very different from one case to another. Those elements which were expelled and mobilized, due to sericitization or chloritization must in such cases vary according to the composition of the original rocks. In such instances, when minerals with hydroxyl groups result anew, the fact ought to be kept in mind that the pH of the mineralising solutions is, in all probability, are of quite decisive importance.

Finally I wish to draw attention to an example of mineral forming processes essentially different from those already discussed, but seeming to offer certain principal similarities with these. D. L. Reynolds has, on the basis of a compilation of analyses, made an attempt to illuminate the various steps in the exchange of substances during granitization (26). This investigation shows for example, that in the case of the formation of hybrid rocks from granite and xenoliths of various varieties but with a composition differing essentially from that of granite, the newly-formed rocks can be enriched in certain components, in relation to the xenoliths as well as to the granite («geochemical culmination» of such components). The fact that during the course of hybridization an average composition of the reacting rocks is thus not immediately obtained, demonstrates that in this case also, the interchange of substances is regulated by certain mineral-associations particularly stable at the prevailing P-T-conditions.

On the basis of the above-mentioned examples the following statement can be made. For an interpretation of the migrations of substances in the upper lithosphere which are often met with in petrological investigations, it would be a matter of great importance if we could establish empirically which are the minerals and mineral associations that appear to be particularly stable under various ranges of temperature, pressure and composition. From our experience on a small scale concerning such mineral associations and migrations occasioned by the mineral forming reactions, it might be possible to interpret the same problem even on a larger scale and also to formulate regular relationships between the different rocks, brought about by various kinds of metamorphic differentiation.

Bibliography.

1. Adams, F. D. and Barlow, A. E., Geology of the Haliburton and Bancroft areas, Province of Ontario. Mem. Geol. Surv. Canada. No. 6, 1910.
2. Backlund, H., Der »Magmaaufstieg« in Faltengebirgen. Bull. Comm. Géol. Finlande, No. 115, 1936, p. 293.
3. Barth, T., Kalk- und Skarngesteine im Urgebirge bei Kristiansand. N. Jahrb. f. Min. etc. Beil.-Bd. LVII, Abt. A, 1928, pp. 1069—1108.
4. —, Zur Genesis der Pegmatite im Urgebirge: II. Ein syntektischer Gesteinskomplex aus dem südlichsten Norwegen. Chemie der Erde, Bd 4, 1928, pp. 95—136.
5. —, Structural and petrologic studies in the Dutchess County, New York. Bull. Geol. Soc. of Am., Vol. 47, 1936, pp. 775—850.
6. —, Correns, C. W., Eskola, P., Die Entstehung der Gesteine, Berlin 1939.
7. Bugge, Jens, The geological importance of diffusion in the solid state. Norsk Videnskapsakademi, Oslo. I. Mat.-nat. Kl., 1945, No. 13.
8. v. Eckermann, H., The rocks and contact minerals of the Mansjö Mountain. Geol. Fören. förh., 44, 1922, pp. 203—410.
9. —, The rocks and contact minerals of Tennberg. Geol. Fören. förh., 45, 1923, pp. 465—537.
10. Eskola, P., On the petrology of the Orijärvi Region in Southwestern Finland. Bull. Comm. Géol. Finlande. No. 40, 1914.
11. —, Om sambandet mellan kemisk och mineralogisk jämvikt hos Orijärvi-traktens metamorfa bergarter. Bull. Comm. Géol. Finlande, No. 44, 1915 (English summary).
12. —, On contact phenomena between gneiss and limestone in Western Massachusetts. Journ. of Geol., XXX, 1922, pp. 265—294.
13. —, On the principles of metamorphic differentiation. Comptes Rendus de la Soc. géol. Finlande, No. 5, 1931.
14. Folinsbee, R. E., Optic properties of cordierite in relation to alkalis in the cordierite-beryl structure. Am. Min., 26, 1941, pp. 485—500.
15. Foslie, S., Hastingsites and amphiboles from the epidote-amphibolite facies. Norsk Geol. tidsskr., 25, 1945, pp. 74—98.
16. Gavelin, S., Adakområdet. Geol. Surv. of Sweden, Ser. C, No. 490, 1947 (English summary).
17. —, Über das Vorkommen von Amphodelith im Skelleftefeld. Geol. Fören. förh., 64, 1942, pp. 456—464.
18. Geijer, P., Falutraktens berggrund och malmer. Geol. Survey of Sweden, Ser. C, No. 275, 1916 (German Summary).
19. —, Gällivare malmfält. Geol. Survey of Sweden, Ser. Ca, No. 22, 1930 (English summary).
20. Goldschmidt, v., Über die metasomatischen Prozesse in Silikatgesteinen. Die Naturwissenschaften, 1922.
21. Magnusson, N. H., Persbergs malmtrakt. Kungl. Kommerskoll, Beskr. över mineralfyndigheter, 2, 1925.
22. —, Långbans malmtrakt. Geol. Survey of Sweden, Ser. Ca, No. 23, 1930 (English summary).

23. Ramberg, H., En undersøgelse av Veststrandens regionalmetamorfe bergarter. Norsk Geol. tidsskr., Bd. 23, 1943, p. 1—174 (English summary).
 24. —, Petrological significance of sub-solidus phase transitions in mixed crystals. Norsk. Geol. tidsskr., Bd 24, 1944, p. 42—74.
 25. —, Litt om diffusjon i de faste bergarter og dens betydning for metamorphose- og metasomatosefenomenene. Geol. Fören. förh., 68, 1946, p. 56—80.
 26. Reynolds, D. L., The sequence of geochemical changes leading to granitization. Quart. Journ. Vol. CII, 1946, p. 389—438.
 27. Rosenquist, I., Metamorphism and metasomatism in the Opdal-Area. Norsk Geol. tidsskr., 22, 1942, p. 106—202.
 28. Stockwell, C. H., An X-ray study of the garnet group. Am. Min., 12, 1927, p. 327—344.
 29. Sundius, N., The optical properties of manganese-poor grünerites and cummingtonites compared with those of manganese-ferous members. Am. Journ. of Science, Vol. XXI, 1931, s. 330—344.
 30. —, Über den sogenannten Eisenanthophyllit der Eulysite. Geol. Surv. of Sweden, Ser. C, No. 374, 1932.
 31. —, Über die Mischungslücken zwischen Anthophyllit-Gedrit, Cummingtonit-Grünerit und Tremolit-Aktinolith. Tscherm. Min. Petr. Mitt., 43, 1933, p. 422—440.
 32. —, The classification of the hornblendes and the solid solution relations in the amphibole group. Geol. Survey of Sweden, Ser. C, No. 480, 1946.
 33. —, Winchell, A. N., Elements of optical mineralogy, II. New York, 1933.
 34. —, A third study of chlorite. Am. Min., 1936, Vol. 21, p. 642—651.
 35. Vogt, Th., Sulitelmafeltets geologi og petrografi. Geol. Survey of Norway, No. 21, 1927.
-

SVERIGES GEOLOGISKA UNDERSÖKNINGS SENAST UTKOMNA PUBLIKATIONER ÄRO:

Ser. Aa. Geologiska kartblad i skalan 1 : 50 000 med beskrivningar.

Priset för karta i ser. Aa med beskrivning är 10:— kr, för karta enbart 8:— kr;

(Price: map sheet + explanation Sw. kr. 10:—, map sheet Sw. kr. 8:—)

- N:o 185 *Hörndal* av R. SANDEGREN och B. ASKLUND. 1943
 » 186 *Möklinta* av R. SANDEGREN och B. ASKLUND. 1946
 » 187 *Vårvik* av R. SANDEGREN och W. LARSSON. Under utgivning.
 » 188 *Avesta* av G. LUNDQVIST och S. HJELMQVIST. 1946
 » 189 *Falun* av O. KULLING och S. HJELMQVIST. 1948
 » 190 *Söderfors* av R. SANDEGREN och B. ASKLUND. 1948
 » 191 *Untra* av R. SANDEGREN och P. H. LUNDEGÅRDH. 1949
 » 192 *Onsala* av R. SANDEGREN och P. H. LUNDEGÅRDH. 1952
 » 193 *Gränna* av P. GEIJER, B. COLLINI, H. MUNTHE och R. SANDEGREN. 1951

Ser. Ad. Agrogeologiska kartblad i skalan 1 : 20 000 med beskrivningar.

Priset för karta i ser. Ad med beskrivning är 8:— kr, för karta enbart 6:— kr;

(Price; map sheet + explanation Sw. kr. 8:—, map sheet Sw. kr. 6:—)

- N:o 1 *Hardeberga* av G. EKSTEDM. 1947

Årsbok 43 (1949)

	Pris
N:o 503 KULLING, OSKAR, Spår av Varangeristiden i Norrbotten. Summary: Traces of the Varanger ice age in the Caledonides of Norrbotten, Northern Sweden. 1951	2,00
» 504 BJÖRSJÖ, N., Israndstudier i södra Bohuslän. Med 2 kartplanscher. Summary: Studies of marginal deposits and of ice borders in South Bohuslän. 1949	7,50
» 505 BROITZEN, F., De geologiska resultatena från borrhningarna vid Höllviken. Del 2: Undre kritan och trias. Med 1 plansch. Summary: The geological results from the deep-borings at Höllviken. Part. 2: Lower Cretaceous and Trias. 1950	3,00
» 506 LUNDBLAD, BRITTA, De geologiska resultatena från borrhningarna vid Höllviken. Del 3: Microbotanical studies of cores from Höllviken, Scania. With 2 plates. 1949	1,50
» 507 LUNDBLAD, BRITTA, De geologiska resultatena från borrhningarna vid Höllviken. Del 4: On the presence of Lepidopteris in cores from »Höllviken II». With 1 plate. 1949	1,50
» 509 KOCZY, F. F., The thorium content of the Cambrian alum shales of Sweden. 1949	1,50
» 510 THORSJÖ, PER, Notes on Kootenia sp. n. and associated Paradoxides species from the lower Middle Cambrian of Jemtland, Sweden. With one plate. 1949	1,50
» 511 WESTERGÅRD, A. H., Non-Agnostidean trilobites of the Middle Cambrian of Sweden. 2. With 8 plates. 1950	4,50
» 512 HJELMQVIST, S., The titaniferous iron-ore deposit of Taberg in the South of Sweden. With one plate. 1950	4,50
» 513 LUNDEGÅRDH, P. H., Aspects to the geochemistry of chromium, cobalt, nickel and zinc. 1949	3,00
» 514 GEIJER, PER, The Rektor ore body at Kiruna. With one plate. 1950 .	1,50

VÄND!

Årsbok 44 (1950)

N:o 515	GRIP, ERLAND, Geology of the sulphide deposits at Menstråk and a comparison with other deposits in the Skellefte district. With 4 plates. 1951	5,00
» 516	ÖDMAN, OLOF, Manganese mineralization in the Ultevis district, Jokkmokk, North Sweden. Part 2. Mineralogical notes. 1950	1,50
» 517	ASKLUND, BROR, Kosteröarna, ett nyckelområde för västra Sveriges prekambriskas geologi. Summary: The Koster isles, a key area for the Pre-Cambrian geology of Western Sweden. Med 2 tavlor. 1950	6,00
» 518	ARRHENIUS, O., Vissa ämnens fördelning i marken i Kopparbergs län. Summary: Some minor elements of the soils in the province of Kopparberg (Dalecarlia). 1952	2,50
» 519	WENNER, C. G., Fjäräs bräcka. 1951	3,00

Årsbok 45 (1951)

» 520	SUNDIUS N., Kvarts, fältspat och glimmer samt förekomster därav i Sverige. 1952	10,00
» 521	GAVELIN, S., Lime metasomatism and metamorphic differentiation in the Adak area	3,50

Ser. Ba.

N:o 13	Berggrundskarta över Stockholmstrakten upprättad av N. Sundius. 1:50 000. 1946	10,00
	Beskrivning till berggrundskarta över Stockholmstrakten av N. Sundius. 1948	5,00
» 14	Jordartskarta över södra och mellersta Sverige. Efter de geologiska kartbladen sammandragen vid S. G. U. av K. E. Sahlström 1:400 000. Mellersta bladet, tryckt 1947	15,00
	Södra bladet, tryckt 1948	15,00
	Norra bladet, tryckt 1949	15,00

Ser. Ca.

N:o 21	LUNDQVIST, G., Beskrivning till jordartskarta över Kopparbergs län. Med karta i skala 1:250 000. 1951	20,00
» 35	GELJER, PER och MAGNUSSON, N. H., De mellansvenska järnmalmernas geologi. Med 56 tavlor. 1944	35,00
» 36	VON ECKERMANN, H., The Alkaline district of Alnö Island (Alnö alkalina område). With 60 plates. 1948	15,00

Rapporter och meddelanden i stencil

1.	Utredning rörande det svenska jordbrukets kalkförsörjning 1—2. 1931 (Kartorna utgådda)	15,00
2.	Sveriges lodade sjöar. Sammanställning av K. E. Sahlström 1945	3,00
3.	Rapport över manganmalmsletningen i Jokkmokks socken 1940—48 av O. H. ÖDMAN. Med 4 kartor	4,00